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OPERATING EXPERIENCE AND DESIGN CRITERIA FOR UNOX WASTEWATER TREATMENT SYSTEMS

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I. BACKGROUND AND INTRODUCTION

The recent and accelerating emphasis on protection of the environment has necessitated the rapid development of improved technology to aid in pollution control. The use of oxygen in place of air in the activated sludge process is one recent advancement in the basic activated sludge process. Its potential in terms of higher quality treatment from existing plants, and construction of new facilities at reduced cost, has resulted in extremely rapid acceptance by municipalities and industry.

The primary distinguishing feature of the UNOX System is that high purity oxygen is the source of oxygen for the micro-organisms in the aeration basin, as opposed to air as the source in conventional activated sludge systems. The concept of using oxygen in this manner is not new, as many investigators have performed work since the early 1940's to demonstrate the feasibility of a high purity oxygen activated sludge process. The major deterrent to oxygen usage in the processes envisaged by these early investigators was economics, centering mainly around the cost of oxygen production, and sufficient utilization of the high purity oxygen to achieve a cost effective system. Notwithstanding this lack of an economically attractive system, enough experimental work was performed by these early workers to indicate many desirable features for systems utilizing a higher purity source of oxygen than for air activated sludge processes.

The Linde Division of Union Carbide Corporation began active experimentation with the use of pure oxygen in the activated sludge process during

the mid-1960's. Bench scale and pilot plant investigation culminated in a full scale demonstration of the UNOX System at Batavia, New York, in 1969, under Federal government sponsorship. The system introduced and demonstrated at Batavia at that time overcame the factors which prevented the use of a pure oxygen activated sludge process from being economically attractive.

At the conclusion of the full scale demonstration at Batavia, New York, the necessity of demonstrating the widespread applicability and highly desirable performance characteristics of the UNOX System on a variety of wastewaters was recognized by Union Carbide. Accordingly, 10 demonstration size pilot plants were constructed and have been operated at nearly 30 locations in the U.S. covering a broad range of wastewater characteristics.

The economic use of oxygen in the activated sludge process requires the availability of relatively inexpensive high purity oxygen gas in tonnage quantities. This capability had been developed in the 1950's in the form of efficient large tonnage cryogenic air separation plants to produce high purity oxygen gas. A substantial distribution network also exists in the United States for bulk quantities of liquid oxygen so that the use of oxygen in activated sludge process was feasible from an oxygen supply standpoint even before the process development to effectively utilize oxygen supply over a broader range through the use of a pressure swing adsorption process to achieve reliable high purity oxygen production in small quantities.

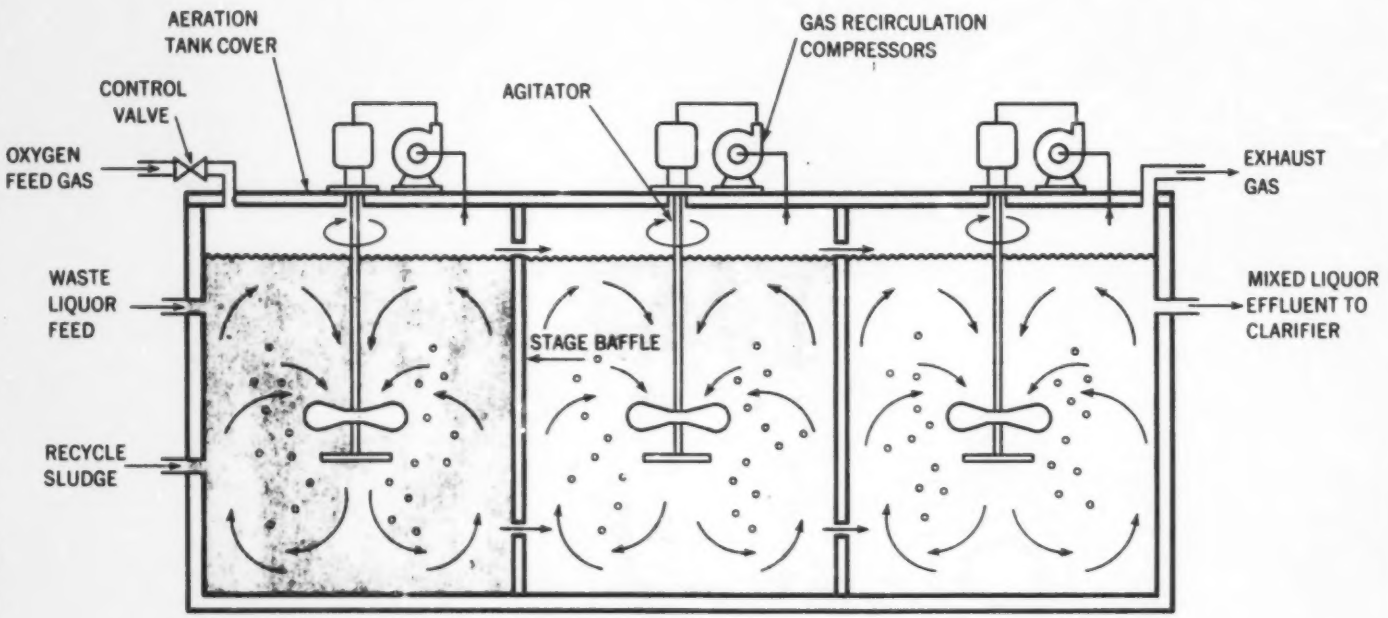
II. UNOX SYSTEM DESCRIPTION

The UNOX System utilizes a covered and staged oxygenation basin (Figure 1) for contact of oxygen gas and mixed liquor. High purity oxygen (90-100% vol.) enters the first stage of the system and flows cocurrently with the wastewater being treated through the oxygenation basin. Pressure under the tank covers is essentially atmospheric, being from 2-4 inches water column, sufficient to maintain control and prevent back mixing from stage to stage. This allows for efficient oxygen utilization at low power requirements. Effluent mixed liquor is separated in conventional gravity clarifiers and the thickened sludge is recycled to the first stage for contact with influent wastewater.

Mass transfer and mixing within each stage is accomplished either with surface aerators or with a submerged turbine rotating sparge system. In the first case, mass transfer occurs in the gas space whilein the latter, gas is sparged into the mixed liquor where mass transfer occurs from the gas bubbles to the bulk liquid. In both cases, the mass transfer process is enhanced by the high oxygen partial pressure maintained under the tank covers in each stage. As a consequence of the increased oxygen partial pressure, it is feasible to maintain higher dissolved oxygen levels in the mixed liquor relative to those achievable with air and to achieve oxygen dissolution with substantially lower energy inputs to the mixed liquor than would be required with air. Thus, the effective transfer efficiency (ETE) of a mass transfer device in oxygen service will be greater than its standard

FIGURE 1

SCHEMATIC DIAGRAM OF UNOX SYSTEM WITH ROTATING SPARGER
(3 STAGES SHOWN)



transfer efficiency (STE), whereas, the opposite is true with the same device operating in air.

The selection of the number of stages, the number of parallel biological reactors, and the type of mass transfer device to employ are variables that depend on waste characteristics, plant size, land availability, treatment requirements and other similar considerations. In practice, the consultant will have essential input to the oxygen system design or in establishing the actual design.

The UNOX System has other important benefits. The maintenance of high D.O. levels with low energy input to the mixed liquor contribute to a highly aerobic biological mass which flocculates well. These factors are responsible for enhanced settling characteristics relative to air systems so that with conventional clarification designs a much higher MLSS level (4000-8000 mg/l) can be carried in the biological reactor than is normally achievable with air activated sludge. This factor is utilized in design to reduce the required reactor detention time while still maintaining a design food to biomass level (F/M) very similar to common practice in air systems. High D.O. levels are also an important factor contributing to lower excess solids production than commonly achieved with air activated sludge systems at comparable biomass loadings.

Since the oxygen gas fed to the system is devoid of nearly all nitrogen and since approximately 90% of the oxygen gas is normally utilized, the total gas venting from the system is only about 1% of the gas vented from an air activated sludge system. Since the reactors are covered, this gas is vented

at one point; thus effective odor control is achieved and the biological aerosol problem typical of air systems is eliminated.

The process control of the UNOX System is very simple. Since the tank is covered, the biological reactor acts essentially as a respirometer. Thus, pressure control can be used to control the oxygen feed rate. A simple pressure sensor is installed in the first stage tank cover which detects changes in gas pressure resulting from a decrease or increase in oxygen uptake as flow or strength changes. A signal is relayed to a flow control valve on the inlet oxygen line which adjusts oxygen flow to maintain the desired gas pressure set point under the first stage cover. Thus, if flow or BOD_5 increases resulting in a lowering of gas pressure in the first stage gas space, the control valve will open causing more oxygen to flow to the system. This simple control circuit provides real time response to the BOD_5 demands placed on the system. It is also possible to automate the oxygen production unit to respond to these changes in demand, thereby causing the system to use only the appropriate power for oxygen generation commensurate with the BOD_5 load being placed on it.

III. OPERATING DATA AND EXPERIENCE

A. Operating Experience

The design of UNOX Systems today is based upon published technology for design of conventional activated sludge processes and upon a very large amount of data accumulated in pilot plant demonstrations and Union Carbide funded development programs. Operating experience with oxygen activated sludge systems commenced with pilot programs prior to the government funded Batavia demonstration work. Since the conclusion of the initial work at Batavia, a very comprehensive pilot plant program has been maintained using a total of 10 pilot plants. These pilot plants have been and are being used throughout the United States (and in certain foreign countries) to demonstrate the UNOX System capabilities to consultants, municipalities, and industries and to obtain design data for the specific waste stream being studied. As of this time, programs have been completed in a total of 21 locations encompassing nearly 15 years of operating experience (Table I). Programs are currently underway in 8 additional locations (Table II).

A typical pilot plant program will involve setting up a pilot plant at the customer's site and assisting the customer's personnel in the operation of the plant. All analytical work is normally performed by the customer at his plant laboratory. Most pilot plant programs have extended over a 4 to 6 month period although some have been conducted for as long as one year. Each program normally includes one phase of operation at steady state flow at approximately the biomass loading anticipated for a system design. Following this, the plant is operated on a diurnal flow cycle to simulate the anticipated hydrau-

TABLE I

PILOT PLANT PROGRAMS

Completed

LOCATION	DURATION (MONTHS)	WASTEWATER TYPE	COMPONENT	CONSULTANT
Northeast	6	Raw Degritted	Domestic	
Batavia, N. Y.	6	Raw Degritted	Dairy Product Processing Domestic	
Mid-Atlantic	5	Primary Effluent	50% Industrial-Chem. Prod. Domestic	
Midwest	3	Primary Effluent Intermediate Trickling Filter Effluent Intermediate Clarifier Effluent	Grain Processing Meat Packing Domestic	
Cincinnati, Ohio	8	Primary Effluent	40% Industrial Domestic	Malcolm Pirnie
Midwest	4	Primary Effluent	Various Industries to 60% Q Domestic	
Grand Island. N.Y.	3	Primary Effluent	Domestic	
Mid-Atlantic	4	Primary Effluent	Chrome Plating Dye Producing Exotic Alloy Mfgs. Domestic	
Louisville, Ky.	9	Primary Effluent Primary Effluent with Industrial	Distilleries, Dairy Products Slaughter Houses, Chemical Mfgs., Domestic	Consoer & Townsend
Miami, Fla.	3	Raw Degritted	Domestic	Miami
Middlesex, N. J.	11	Raw Degritted	Pulp & Paper Mfgs., Food Processors, Chemical Mfgs. Plastics, Domestic	Metcalf & Eddy
Southeast	2	Raw Degritted	Textile, Poultry Processing, Domestic	
New Orleans, La.	6	Raw Degritted	Breweries, Seafood Processing Poultry Processing, Domestic	W. S. Nelson
Northeast	8	Raw Degritted	Pulp & Paper Mfg., Plastics Producers, Domestics	
Northeast	9	Primary Effluent	60% Industrial 40% Domestic	
Northwest	5	Primary Effluent	Domestic, Canning Waste	
South Charleston, W.Va.	3	Primary Effluent	Petrochemical, Domestic	UCC
West	3	Primary Effluent	Domestic, Canning Waste	
Midwest	6	Primary Effluent	Industrial - Chemical, Dairy, Brewery, Food, Domestic	
Taft, La.	9	Lagoon Effluent	Petrochemical	UCC
Northeast	4	Raw Degritted	Chemical Producers, Coke Producers, Refineries, Domestic	

TABLE II

PILOT PLANT PROGRAMS

In Operation

LOCATION	WASTEWATER TYPE	COMPONENTS
Blue Plains, Washington, D. C.	Primary Effluent	Domestic
Mid-Atlantic	Primary Effluent	Pulp & Paper Mill Process Waste
West	Primary Effluent	Canning Process Water 50% Industrial Domestic
Northeast	Primary Effluent	Organic Dye Production (30%) Domestic
Northeast	Primary Effluent	Domestic
Northeast	Primary Effluent	Combined Industrial (60%) Domestic
Southeast	Primary Effluent	Domestic
Midwest	Primary Effluent	Domestic

lic pattern expected at the site. Subsequent operational phases will include sustained operation at high biomass loadings or high hydraulic flows to simulate more severe conditions than normally expected in the actual design. During each operating phase a full complement of data is taken in the plant by regularly sampling influent, effluent, mixed liquor, recycle and sludge waste streams and by reading all plant operating indicators on a regular 24 hour basis, 7 days per week.

Two types of pilot plants are used in these applications. The majority of the plants are mounted within 40-foot warehouse van trailers so that they can be easily transported around the country and simply placed into operation. The others are somewhat smaller portable plants which can be relocated quite easily but require a building for weather protection, as well as slightly more extensive installation service than is required for the mobile plants. The mobile plant has a nominal capacity of up to 43,000GPD, whereas the portables operate at up to about 7500GPD.

The mobile unit is a completely enclosed secondary wastewater treatment system with an external secondary clarification unit. All tankage, instrumentation and controls, pumps, and a small laboratory are contained within the forty foot warehouse van trailer. A schematic diagram of the unit is presented in Figure 2.

As indicated, the oxygenation tankage in the mobile pilot facility is divided into four sections or stages by means of baffles and is covered to provide a gas tight enclosure. The liquid and gas phases flow concurrently through the system. Raw wastewater, recycle sludge and oxygen gas

are introduced into the first stage. The pilot unit has the flexibility to be operated as a two, three, or four stage system. The number of stages utilized may vary dependent on the specific application. Each of the stages is a completely mixed unit with the overall four stage system approximating a plug flow type reactor. The wastewater and the biomass return are mixed upon entering the first stage. The pilot plant wastewater feed and sludge recycle pumps are calibrated, variable speed units. Their operating speeds are used to monitor the influent and recycle flows.

During operation, high purity oxygen gas is fed into the first stage gas space; the gas pressure is maintained at about one inch of water above the atmospheric. The oxygen enriched gas flows through interstage gas passages and is vented to the atmosphere through a volumetric flow meter. The slight pressure drop between successive stages is sufficient to prevent backmixing of the oxygen enriched gas. The stagewise gas phase oxygen compositions are periodically measured with a paramagnetic oxygen analyzer. As the oxygen enriched atmosphere passes through the system, small diaphragm compressors in each stage pump the gas down the hollow mixer shaft and through the roatating sparger at a rate sufficient to maintain a dissolved oxygen concentration of approximately 7 mg/l. The oxygen gas feed is volumetrically measured and automatically controlled by the gas phase pressure in the first stage.

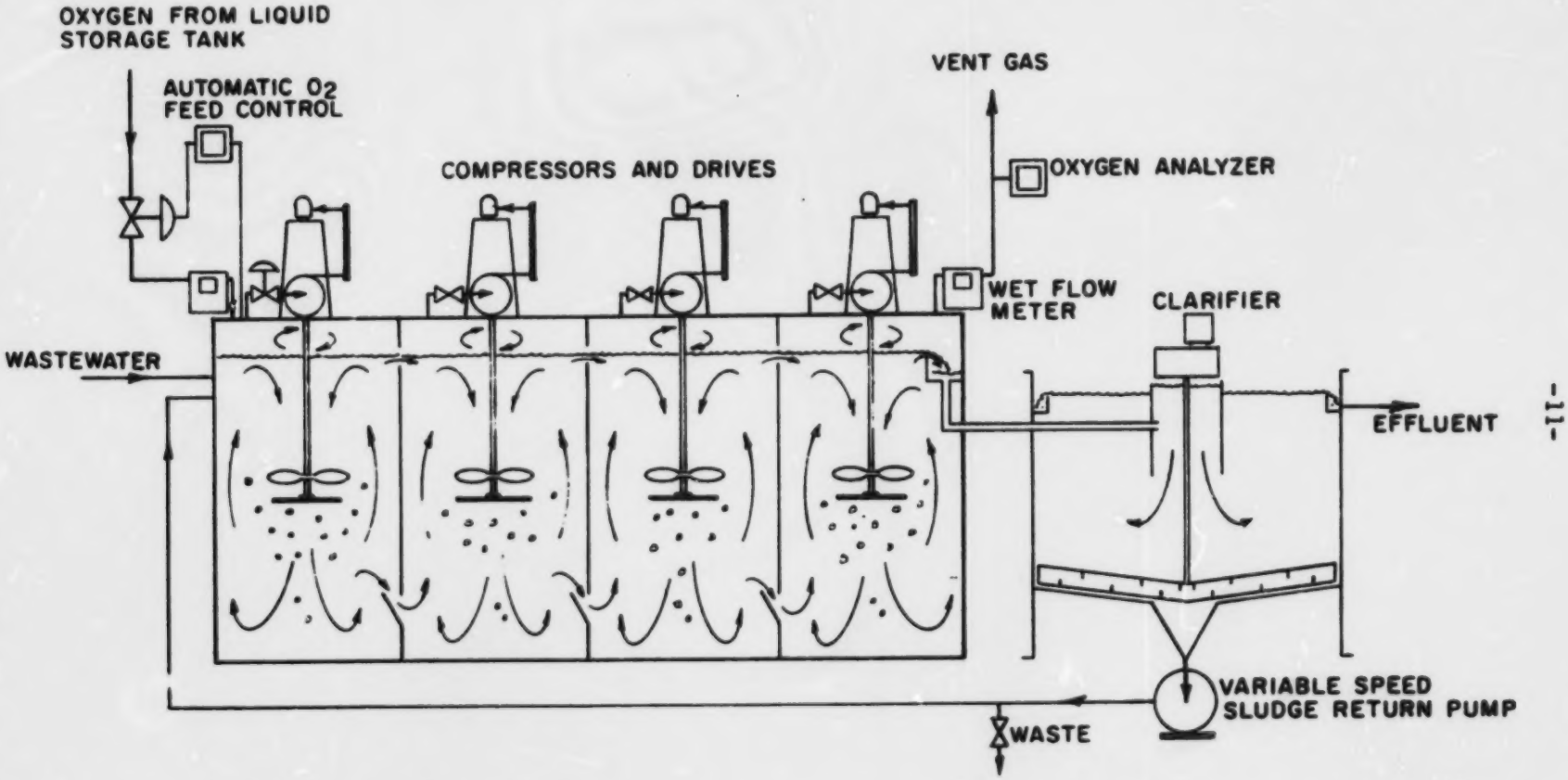
Effluent from the biological reactor flows to a center feed clarifier which contains a peripheral effluent weir. The clarifier contains a plow type scraper with a center take-off for settled solids.

In addition to the monitoring of gas and the liquid flows by appropriate

FIGURE 2

MOBILE PILOT PLANT SCHEMATIC

"UNOX" SYSTEM



BIOLOGICAL REACTOR

Liquid Depth	5'2"
Stage Volume	400 gal.
Total Liquid Volume	1600 gal.

SECONDARY CLARIFIER

Diameter	7 ft.
Side Water Depth	9 ft.
Center Well Diameter	26 in.
Overflow Area	33.2 ft^2

metering and recording equipment, several basic parameters are measured to determine the system performance. Composite samples of the bioreactor influent, the clarifier effluent, and the sludge recycle are formed from grab samples taken frequently. Wastewater flow and gas flow measurements are taken to correspond to each of the composites formed.

Grab samples of the mixed-liquor from Stages 1 and 4 are taken three times daily for solids and settling tests. Solids are wasted from the clarifier on a semi-continuous basis in an attempt to approximate a full scale system. The volumes wasted are measured and grab samples of the solids recycle are taken for solids analysis. Grab samples are also taken from Stages 2 and 3 once each day for solids analysis. Virtually all of the analytical procedures are carried out as prescribed in the 12th Edition of Standard Methods.

B. Results from Specific Programs

The results from many of these pilot plant operations is included in Tables III to VII.

C. Correlation of Results for Design

From the results of the large number of programs already completed and from the design information available on conventional activated sludge, it is possible to develop some useful relationships of value in design of a UNOX System for a specific waste stream. The most important of these relationships include substrate removal, oxygen requirements, excess solids production, and solids-liquid separation characteristics.

1) Substrate Removal

The design of UNOX Systems is closely keyed to the use of

TABLE III
"UNOX" SYSTEM
PILOT TEST DATA

PERFORMANCE SUMMARY

		UNITS	LOCATION A		LOCATION B	
			PHASE I	PHASE II	PHASE I	PHASE II
Retention Time, (Q)		Hrs.	1.8	1.6 (0.89-2.1)	1.8	2.0
Recycle Ratio (R/Q)		%	28	28	37	.30
Sewage Temperature		°F	57	66	84	80
Mixed-Liquor SS		mg/l	6100	4000	5060	7010
VSS/TSS			0.62	0.74	0.76	0.77
Organic Loading (Lbs. BOD/1000 cu. ft-day)		-	165	190	198	171
Biomass Loading (Lbs. BOD/Lbs. MLVSS-day		-	0.66	1.02	.83	0.50
Influent Characteristics:	COD	mg/l	375	365	471	467
	BOD_5	mg/l	185	200	238	227
	SS	mg/l	180	135	83	76
Effluent Characteristics:	COD	mg/l	88	72	106	81
	BOD_5	mg/l	21	17	10	8
	SS	mg/l	20	16	27	15
Removals:	COD	%	77	80	76	82
	BOD_5	%	89	92	95	96
	SS	%	89	88	64	80
Clarifier Overflow Rate		gal/ft^2-day	660	710 (520-1300)	650	582
Clarifier Mass Loading		Lb. SS/ft^2-day	45	29 (23-75)	27.3	44.5
Clarifier Underflow Conc.		%	2.6	1.7	1.9	3.13
Sludge Volume Index		-	40	61	55	42
Lbs. VSS/Lb. BOD_5 Removed						
Accumulation		-	0.718	0.581	.42	.367
For Disposal		-	0.64	0.515	.33	.272
Lbs. O_2/Lb. BOD_5 Removed		-	0.89	0.94	1.32	1.35
Lbs. O_2/Lb. COD Removed		-	0.689	0.602	.72	0.77
COD/BOD Ratio		-	2.08	1.83	2.42	2.06
SRT		-	2.11	1.69	2.87	5.45

TABLE IV
"UNOX" SYSTEM
PILOT TEST DATA

PERFORMANCE SUMMARY

		UNITS	LOCATION C PHASE I	LOCATION C PHASE II	LOCATION D PHASE I
Retention Time, (Q)		Hrs.	1.8	1.07	2.2 (1.4-3.2)
Recycle Ratio (R/Q)		%	30	22	31
Sewage Temperature		°F	75	72	67
Mixed-Liquor SS		mg/l	5800	4900	6200
VSS/TSS			0.8	0.79	0.77
Organic Loading (Lbs. BOD/1000 cu. ft-day)		-	147	208	143
Biomass Loading (Lbs. BOD/Lbs. MLVSS-day		-	0.51	0.85	0.48
Influent Characteristics:	COD	mg/l	460	392	454
	BOD_5	mg/l	177	145	209
	SS	mg/l	143	120	126
Effluent Characteristics:	COD	mg/l	124	181	90
	BOD_5	mg/l	14	19	11
	SS	mg/l	36	31	30
Removals:	COD	%	73	54	80
	BOD_5	%	91	87	95
	SS	%	75	74	76
Clarifier Overflow Rate		gal/ft^2-day	640	1085	529 (350-800)
Clarifier Mass Loading		Lb. SS/ft^2-day	40	53	32.6
Clarifier Underflow Conc.		%	2.3	3.0	2.3
Sludge Volume Index		-	47	41	56
Lbs. VSS/Lb. BOD_5 Removed					
Accumulation		-	0.52	0.83	0.64
For Disposal		-	0.33	0.62	0.50
Lbs. O_2/Lb. BOD_5 Removed		-	1.32	1.23	1.06
Lbs. O_2/Lb. COD Removed		-	0.64	0.73	0.58
COD/BOD Ratio		-	2.6	2.7	2.17
SRT		-	3.75	1.42	3.36

TABLE V
"UNOX" SYSTEM
PILOT TEST DATA

PERFORMANCE SUMMARY

		UNITS	LOCATION E		LOCATION F	
			PHASE I	PHASE II	PHASE I	PHASE II
Retention Time, (Q)		Hrs.	1.8	1.8*	1.7 (1.1-2.8)	1.3 (1.2-1.5)
Recycle Ratio (R/Q)		%	25	26	27	26
Sewage Temperature		°F	70	78	87	87
Mixed-Liquor SS		mg/l	5600	7350	6200	5950
VSS/TSS			0.66	0.74	0.75	0.83
Organic Loading (Lbs. BOD/1000 cu. ft-day)		-	181	193	162	196
Biomass Loading (Lbs. BOD/Lbs. MLVSS-day		-	0.76	0.56	0.55	0.64
Influent Characteristics:	COD	mg/l	308	377	380	398
	BOD_5	mg/l	210	229	184	170
	SS	mg/l	191	236	183	172
Effluent Characteristics:	COD	mg/l	64	66	67	63
	BOD_5	mg/l	12	12	6	5
	SS	mg/l	18	28	17	13
Removals:	COD	%	79	82	82	84
	BOD_5	%	94	95	97	97
	SS	%	98	88	91	92
Clarifier Overflow Rate		gal/ft^2-day	650	650	730(420-1060)	890 (780-1000)
Clarifier Mass Loading		Lb. SS/ft^2-day	37	50	41	52
Clarifier Underflow Conc.		%	2.5	3.2	2.7	2.3
Sludge Volume Index		-	79	48	55	55
Lbs. VSS/Lb. BOD_5 Removed						
Accumulation		-	0.53	0.38	0.31	0.36
For Disposal		-	0.45	0.27	-	-
Lbs. O_2/Lb. BOD_5 Removed		-	0.81	1.03	1.22	1.07
Lbs. O_2/Lb. COD Removed		-	0.65	0.72	0.70	0.53
COD/BOD Ratio		-	1.47	1.64	2.06	2.32
SRT		-	2.5	4.7	5.85	4.25

TABLE VI
"UNOX" SYSTEM
PILOT TEST DATA

PERFORMANCE SUMMARY

		UNITS	LOCATION G PHASE I	LOCATION H PHASE I	LOCATION H PHASE II
Retention Time, (Q)		Hrs.	1.8	1.8	2.2
Recycle Ratio (R/Q)		%	36	33	33
Sewage Temperature		°F	70	96	94
Mixed-Liquor SS		mg/l	4190	5300	6600
VSS/TSS			0.79	0.88	0.9
Organic Loading (Lbs. BOD/1000 cu. ft-day)		-	145	230	200
Biomass Loading (Lbs. BOD/Lbs. MLVSS-day		-	.72	0.89	0.54
Influent Characteristics:	COD	mg/l	321	893	888
	BOD_5	mg/l	177	274	294
	SS	mg/l	90	84	79
Effluent Characteristics:	COD	mg/l	60	425	357
	BOD_5	mg/l	13	22	27
	SS	mg/l	25	19	46
Removals:	COD	%	84	52	60
	BOD_5	%	93	92	90
	SS	%	71	42	40
Clarifier Overflow Rate		gal/ft^2-day	650	650	520
Clarifier Mass Loading		Lb. SS/ft^2-day	30.1	33	34
Clarifier Underflow Conc.		%	1.47	2.0	2.7
Sludge Volume Index		-	64	90	130
Lbs. VSS/Lb. BOD_5 Removed					
Accumulation		-	.60	0.36	0.41
For Disposal		-	.49	0.2	0.26
Lbs. O_2/Lb. BOD_5 Removed		-	.93	1.28	1.46
Lbs. O_2/Lb. COD Removed		-	.71	0.68	0.73
COD/BOD Ratio		-	1.81	3.35	3.0
SRT		-	2.33	3.52	4.5

TABLE VII
"UNOX" SYSTEM
PILOT TEST DATA

PERFORMANCE SUMMARY

		UNITS	LOCATION I PHASE I	LOCATION I PHASE II*	LOCATION I PHASE I*	LOCATION I PHASE II
Retention Time, (Q)		Hrs.	1.8	1.85	1.5	0.75
Recycle Ratio (R/Q)		%	29	42	25	25
Sewage Temperature		°F	65	64	73	64
Mixed-Liquor SS		mg/l	4700	4200	4000	4200
VSS/TSS			0.84	0.85	0.72	0.76
Organic Loading (Lbs. BOD/1000 cu. ft-day)		-	350	280	117	286
Biomass Loading (Lbs. BOD/Lbs. MLVSS-day		-	1.4	1.2	0.67	1.44
Influent Characteristics:	COD	mg/l	826	825	260	400
	BOD_5	mg/l	415	331	133	143
	SS	mg/l	180	386	160	136
Effluent Characteristics:	COD	mg/l	99	132	57	95
	BOD_5	mg/l	12	23	11	15
	SS	mg/l	18	42	19	32
Removals:	COD	%	88	84	78	76
	BOD_5	%	97	93	92	89
	SS	%	90	89	87	77
Clarifier Overflow Rate		gal/ft^2-day	520	530	588	782
Clarifier Mass Loading		Lb. SS/ft^2-day	31.0	26.0	24.1	34.2
Clarifier Underflow Conc.		%	1.5	1.3	1.9	1.8
Sludge Volume Index		-	82	85	106	94
Lbs. VSS/Lb. BOD_5 Removed						
Accumulation		-	.67	1.23	0.61	1.10
For Disposal		-	.64	1.08	0.46	0.86
Lbs. O_2/Lb. BOD_5 Removed		-	0.85	0.90	1.60**	0.98
Lbs. O_2/Lb. COD Removed		-	0.42	0.36	0.86	0.40
COD/BOD Ratio		-	2.00	2.50	1.95	2.80
SRT		-	1.06	0.68	2.44	0.63

* Unclarified trickle filter effluent
** Partial Nitrification occurring.

biomass loading as a parameter for design. Conventional air activated sludge process are typically designed for biomass loadings of 0.3 to 0.5 based on volatile solids in most cases. This range of operation represents an equitable balance between retention time and sludge accumulation and provides for a stable operating mode. UNOX Systems generally are designed on the same basis except that the range of biomass loadings is somewhat higher. Most designs are made at average biomass loadings of 0.5 - 0.8. When oxygen is not limiting, it is possible to design at this increased level due to the enhanced ability to transfer oxygen to support metabolism without destructively high energy inputs to the mixed liquor. Figure 3 presents the data correlating F/M removed against phase average biomass loading for pilot plant results previously presented in Figures 3 to 7. The slope of the line represents the percentage BOD_5 removal.

The range of secondary system removals varied from 87 to 97 percent for all programs presented as a group for phase average biomass loadings as high as 1.4. It is evident that the process can be reliably sustained and achieve high substrate removal at the design average biomass loading range of 0.5 - 0.8. The figure also shows that the process will perform well during diurnal or peak organic load periods (represented by phase average data, as high as 1.4) when biomass loadings will exceed the design range for some period of time provided oxygen is not limiting. This is important in maintaining consistently high quality treatment.

FIGURE 3

"UNOX" SYSTEM

Organic Removal as a Function of
Biomass Loading

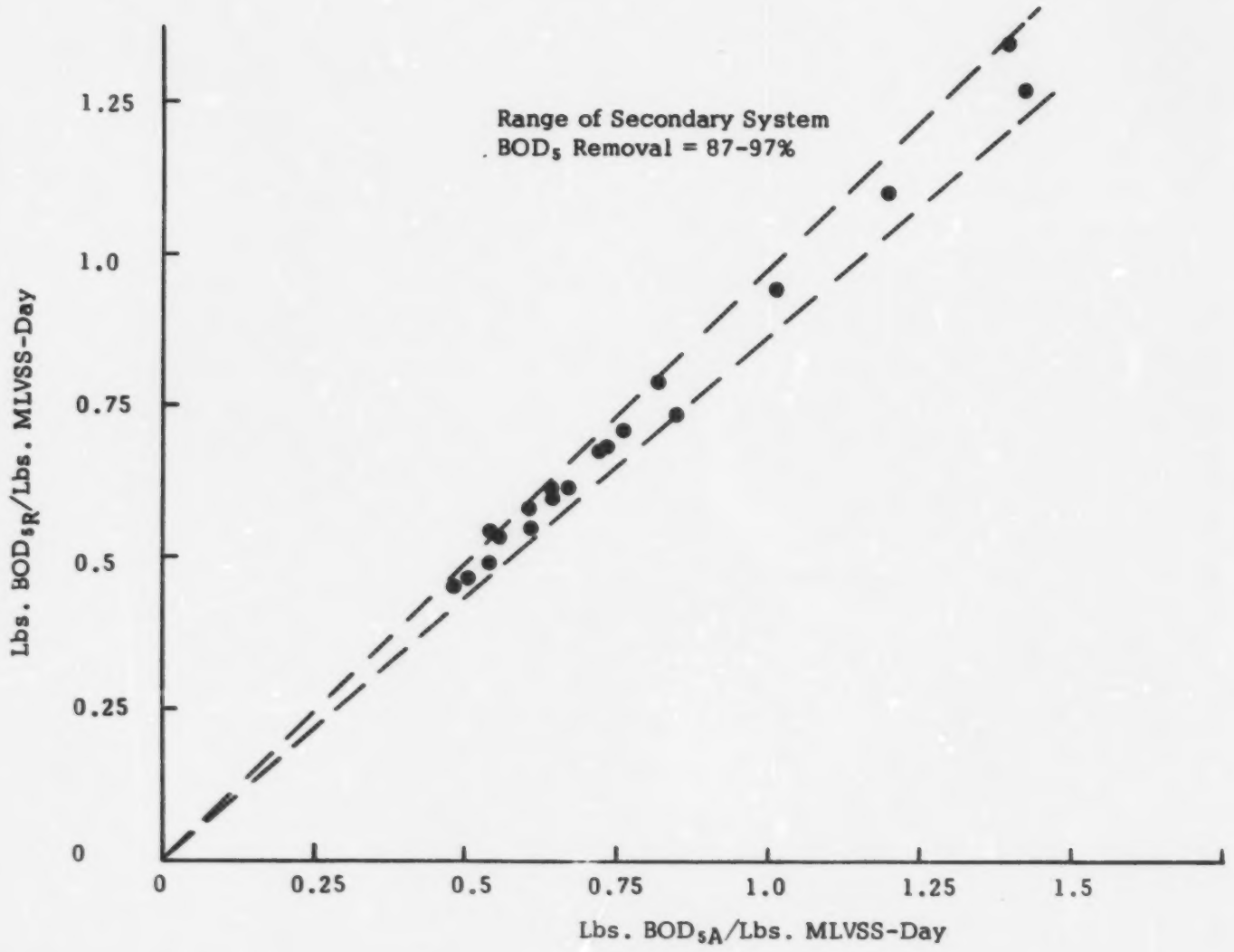


FIGURE 4

"UNOX" SYSTEM

Organic Removal as a Function of Organic Loading

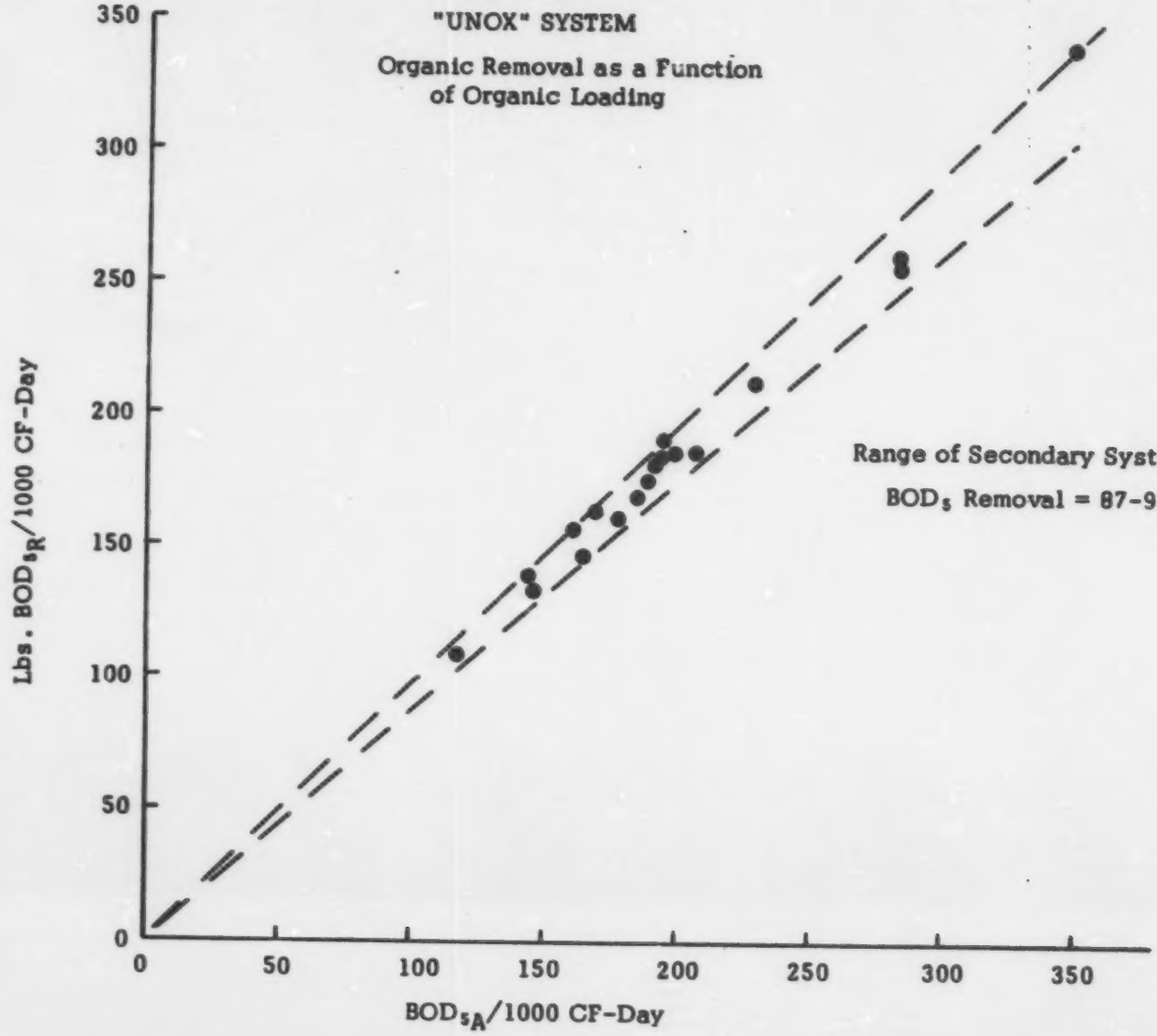


Figure 4 is a comparable presentation of the data based on the organic loading parameter, Lbs. of BOD_5/1000 ft^3 oxygenation tankage/day.

2) Oxygen Requirements

The total oxygen requirements in the activated sludge system are related to the oxygen required for synthesis and that associated with endogenous respiration. Since the UNOX System is a closed system, and oxygen containing gas is monitored for both flow and concentration, it is apparent that one may readily determine the oxygen consumed per unit of BOD_5 removed. Figure 5 presents a correlation of oxygen consumption per unit BOD_5 removal as a function of biomass loading for several plants and types of waste. At high food to microorganism ratios, oxygen requirement per unit BOD_5 removal is governed mainly by oxygen required for cell synthesis, since the degree of endogenous respiration is relatively low as is indicated by higher excess sludge production at high food to microorganism ratios. At low food to microorganism ratios the degree of autooxidation increases, the oxygen requirement increases, and the quantity of excess sludge produced decreases.

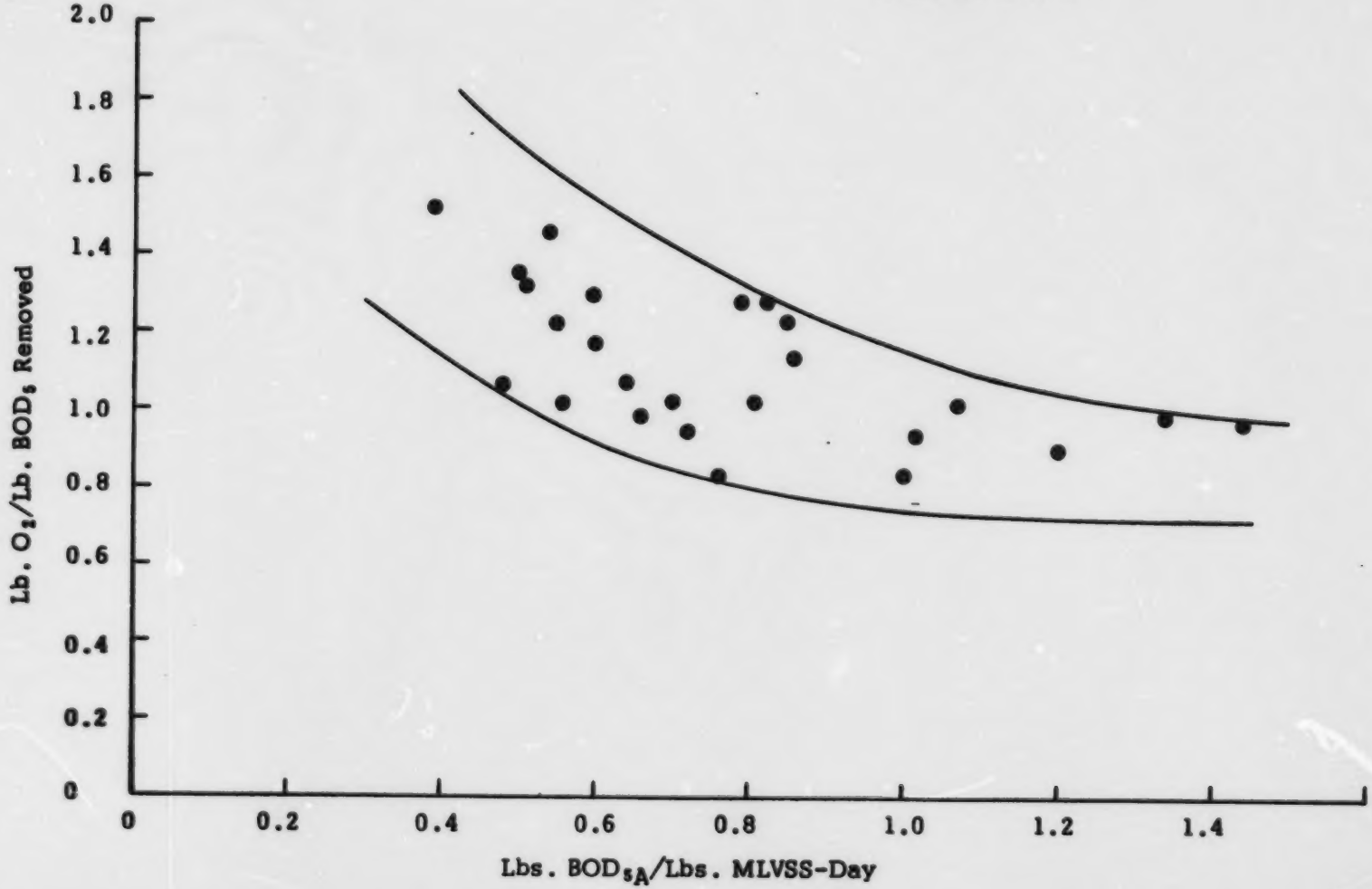
A second, and most important factor, for determining the oxygen requirement is the COD/BOD_5 ratio. Increasing the COD/BOD_5 ratio results in increasing the oxygen consumption per unit removal which is opposite to the effect of increasing F/M.

Chemical oxygen demand measures the total oxidation potential of the wastewater substrate. This test includes biodegradable materials, as well as non-biodegradable or refractory substances. The

FIGURE 5

"UNOX" SYSTEM

Oxygen Consumption as a Function of F/M



BOD_5 test measures some fraction of the biodegradability relative to the COD. In an activated sludge process the amount of substrate removed biologically will generally exceed the indicated BOD_5. This incremental removal in excess of the measured influent BOD_5 represents biodegradable COD not entirely detected in the standard BOD_5 test. Thus, the COD/BOD_5 ratio is indicative of the relative (biological) toughness and total organic strength of of the waste.

Within any activated sludge system the microorganisms attack all of the organic substrate available to them, not only BOD_5, but also BOD_{20}, BOD_{100}, etc., (almost) all of which are included in the COD measure. The BOD_5 being relatively easy to degrade, is almost completely assimilated; whereas a smaller portion of the BOD_{20} (hard to degrade) is assimilated, and most of the BOD_{100} (very hard to degrade) will pass through the system unaffected.

As the COD to BOD_5 ratio in the influent increases, our data from UNOX pilot plants indicates that a higher quantity (poundage) of the COD will be biologically removed even though it is not indicated in the BOD_5 test. Consequently, more oxygen is required per unit BOD_5 removed, however, on a COD removal basis, oxygen consumption will remain relatively stable over the design range of food to microorganism ratios employed.

Figure 5 represents the band of data that will result from oxygen consumption per unit BOD_5 removal when both F/M and COD/BOD_5 ratios are investigated.

3) Excess Sludge Production

The extent of net or excess solids production is a function of the degree of endogenous respiration occurring in the oxygenation system.

The degree of endogenous respiration is governed by the food to microorganism ratio. Since the UNOX System employs a multistage gas-liquid contacting approach with all streams entering the first stage, the food to microorganism ratio decreases rapidly from stage to stage. Therefore, a high degree of stabilization is occurring in the latter stages resulting in decreased sludge production. It has also been determined that a high dissolved oxygen environment will result in a lower sludge yield due to the highly aerobic character of the biological floc. In essence, this means that all floc particles are in a working mode and when placed in a food limiting situation, will therefore undergo a higher degree of endogenous respiration or autooxidation than floc in a low D.O. environment. The measurement of sludge production in any biological process is difficult and requires careful control of wasting schedules and system sludge inventory levels, as well as careful analytical monitoring of the system. If care is not taken, misleading results can easily be obtained. In UNOX pilot plant programs extensive solids production data is regularly taken.

Figure 6 represents a relationship between excess sludge production and solids retention time which has been developed from some of the UNOX programs. As indicated, sludge production increases as the SRT decreases (food to biomass ratio increases). Higher biomass loadings result in an increase in cell synthesis and a decrease in endogenous respiration. The phase average data points presented have been corrected for changes in system inventory due to solids accumulation or losses which may be attributed to sludge production.

It is difficult to correlate excess sludge production for a wide variety of wastewaters since there are other determining factors to consider when attempting to predict production figures. One must account for 1) the fraction of volatile suspended matter entering the unit which is non-biodegradable, 2) the temperature effect on the degree of endogenous respiration, and 3) the quantity of organic material oxidized, not just the BOD_5 removal. This is in essence the effect of the COD/BOD_5 ratio and, of course, the source of the waste itself. In every instance where UNOX and air activated sludge systems have been operated on a side-by-side basis, the net solids production from the UNOX System has been significantly lower.

4) Solids-Liquid Separation

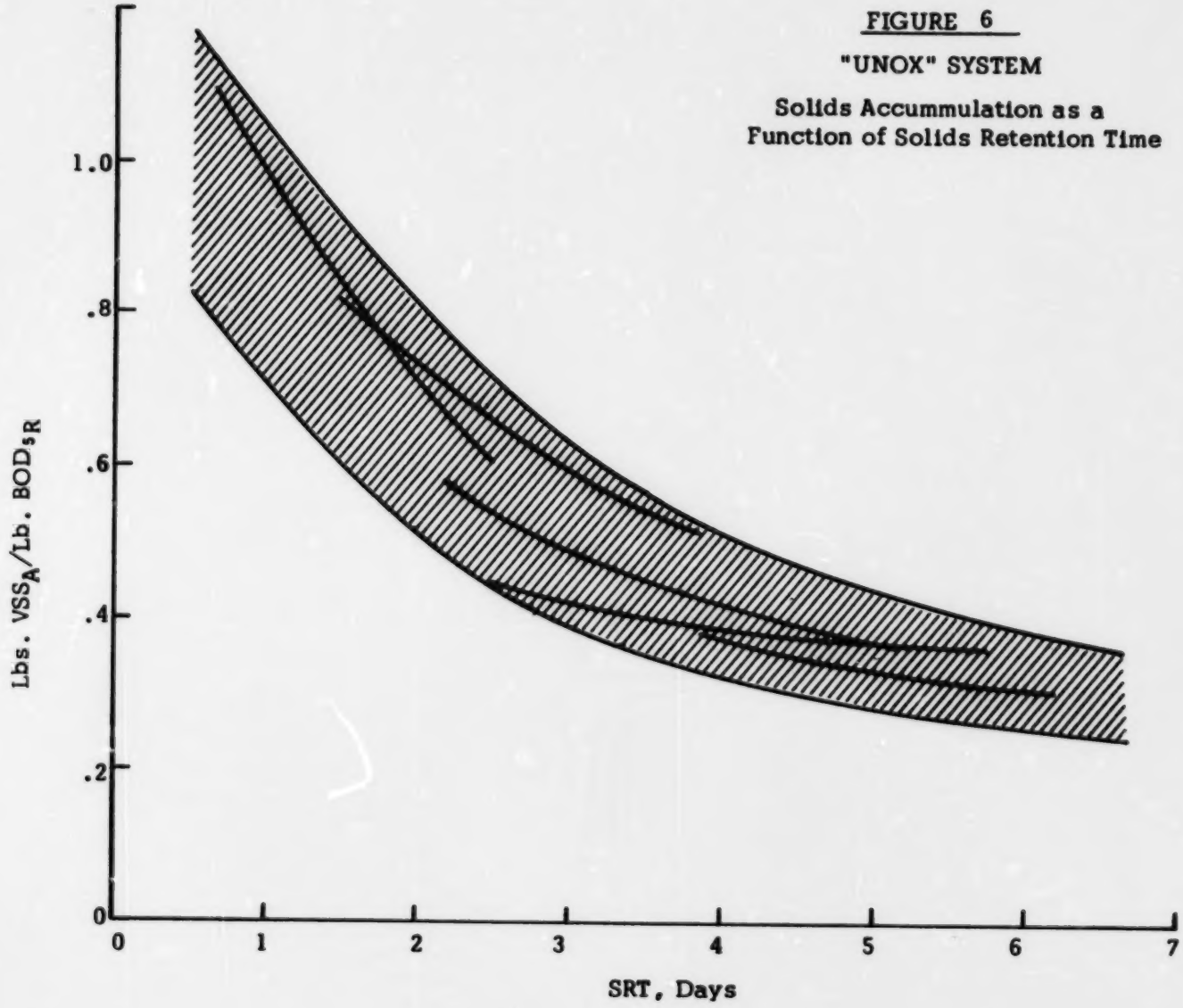
The importance of solids-liquid separation to the waste treatment field cannot be overemphasized. Most often the success of a waste treatment plant depends on the success of the solids-liquid separation equipment. This is especially true for the activated sludge process where, efficient performance of the final settling tanks is imperative because the solids must be recycled to the aeration basins to sustain the process, and any solids escaping separation will impair the quality of the effluent.

The performance of the secondary gravity clarifier used in biological treatment processes such as in the activated sludge process is related to both the physical and chemical nature of the sludge and to the hydraulic characteristics of the clarifier. For the activated sludge process to be successful, the clarifier must serve the dual functions of clarifying the liquid overflow and thickening the sludge underflow. The clarification capacity of the unit is related to the initial settling velocity of the sludge.

FIGURE 6

"UNOX" SYSTEM

Solids Accummulation as a
Function of Solids Retention Time



Conventionally, the area required for clarification of a suspension with hindered settling is estimated such that the vertical liquid rise rate in the clarifier is less than the solids subsidence rate over the operating mixed liquor suspended solids range. In other words, the allowable overflow rate in this case can be calculated by:

$$OR = \frac{180\ (ISV)}{S.F.}$$

WHERE,

ISV = initial (zone) settling velocity of the mixed liquor, ft/hr

OR = allowable overflow rate, GPD/ft^2

S.F.= safety factor applied

The area required for sludge thickening, on the other hand, is related to the solids flux or mass loading that the clarifier would be able to handle under gravity. An analysis of the solids flux in a batch gravity settling tank was given by Kynch. Dick proposed a similar analysis to determine the limiting solids flux in a continuous gravity thickener or clarifier. In both Kynch's and Dick's analysis, the basic assumptions were made:

- At any point in the dispersion within the gravity settling tank, the velocity of fall, i.e. the settling velocity of a particle depends on the local concentration of particles;
- The local concentration of particles is uniform in the radial or horizontal direction or layer;
- Wall effects can be ignored; and
- The particles are of the same type

With the previous assumptions, the settling process occurring in the thickening zone of a gravity settling tank can be described using a continuity equation (a solids mass balance in the vertical direction) without knowing the details of the forces acting on the particles.

We now assume that one can express the settling velocity V_i solely as a function of solids concentration C_i by the following equation.

$$V_i = A\, C_i^{-n}$$

Where, A and n are constants obtained from settling data.

This equation implies that a plot of V_i vs. C_i will form a straight line on log-log paper with a negative slope. Some of the settling data presented by Dick seem to support this assumption. To obtain data for UNOX Systems a plexiglass settling column 5-1/2" ID by 8-1/2' length was constructed with a stirring mechanism and sample taps along the length of the column, and was used to obtain settling data in many of the demonstration plants. The results of these tests are portrayed in Figure 7. The band of data entitled UNOX sludges cover a wide range of waste streams in many locations at varying temperatures and biomass loadings. Activated sludge developed in raw degritted wastewater will settle somewhat better than a sludge developed on primary effluent so the right hand side of the data band represents raw wastewater activated sludges or low VSS/TSS sludges. Activated sludges generated from primary effluent wastes will settle with characteristics more typical of the left hand side of the data band. With the data it is possible to closely predict the expected settling characteristics for a given waste and, therefore, develop a consistent design for both the biological reactors and the clarifier.

The interaction of the clarifier with the reactor is very critical to design and reliable operation of any activated sludge process. The design flexibility is shown clearly in Figure 8 which shows the relationship between clarifier overflow rate and system solids concentrations. The figure indicates the tradeoffs available to the designer in selection of low clarifier overflow rates to achieve very high MLSS and recycle sludge concentrations or in selecting higher overflow rates with somewhat decreased MLSS and recycle sludge concentrations. The same curve is also useful in evaluating plant operation as a function of hydraulic cycles as clarifier overflow rates change with a corresponding change in system MLSS and recycle sludge concentrations. Such fluctuations are important design considerations. Figure 8 is drawn at a constant recycle fraction of 30%. A discrete band exists for any recycle fraction. MLSS will increase with increasing R/Q while recycle sludge concentration will decrease.

There are a limited amount of initial settling velocity data, especially data covering a wide range of solids concentrations for air activated sludge in the open literature. Katz, et al, presents a plot of settling rate vs. initial solids concentration for an activated sludge without giving any more details. Dick, et al, report settling data obtained in three activated sludge plants, but again no details are given about the plants themselves. Dick also uses a "typical" settling velocity vs. concentrations plot in his illustration problems when he discusses thickening in secondary clarifiers. From these sources we have come up with a range of settling velocities vs. concentrations relationships which might be representative of the air activated

sludge zone settling characteristics. Where the initial settling velocity (ISV) is plotted against the initial solids concentration both for air and UNOX sludges, the UNOX sludges have higher ISV over the entire range of the sludge concentrations of interest (Figure 7). The general effect on system performance is shown in Figure 9 where MLSS and recycle sludge concentrations are shown for typical air and oxygen systems as a function of clarifier overflow rate.

The data presented on UNOX Systems was obtained for biomass developed from primary effluent wastewaters. The expected settling velocities would be higher than indicated in Figure 7 for biomass developed from degritted wastewater so that higher MLSS concentrations can be expected than shown in Figures 8 and 9 at comparable overflow rates.

FIGURE 7
SETTLING CHARACTERISTICS FOR
AIR AND OXYGEN BIOMASS
(ISR VS CONCENTRATION)

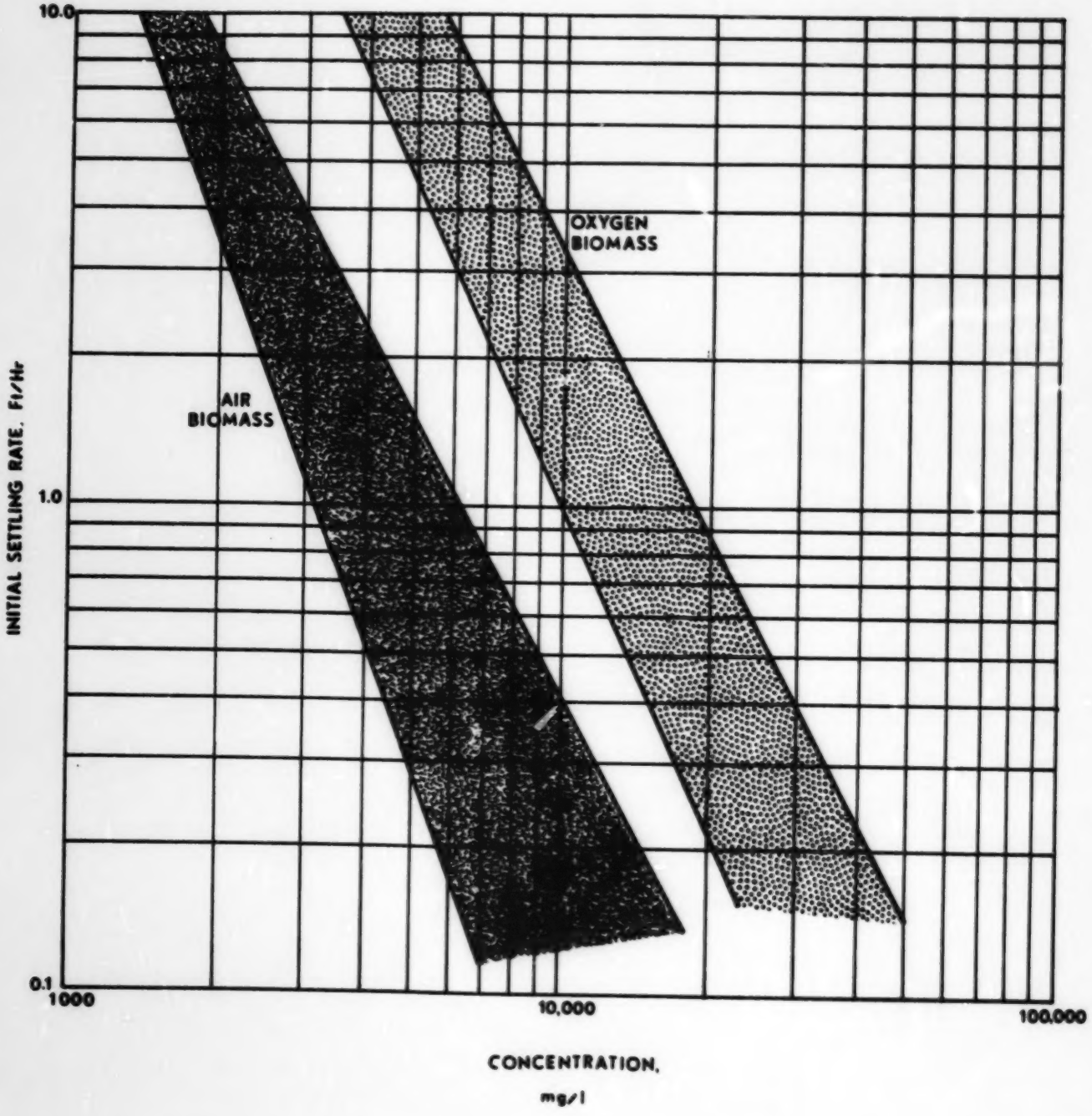


FIGURE 8

PREDICTED SECONDARY CLARIFIER PERFORMANCE
OF "UNOX" SYSTEMS TREATING
PRIMARY EFFLUENT WASTES
(at 30% R/Q)

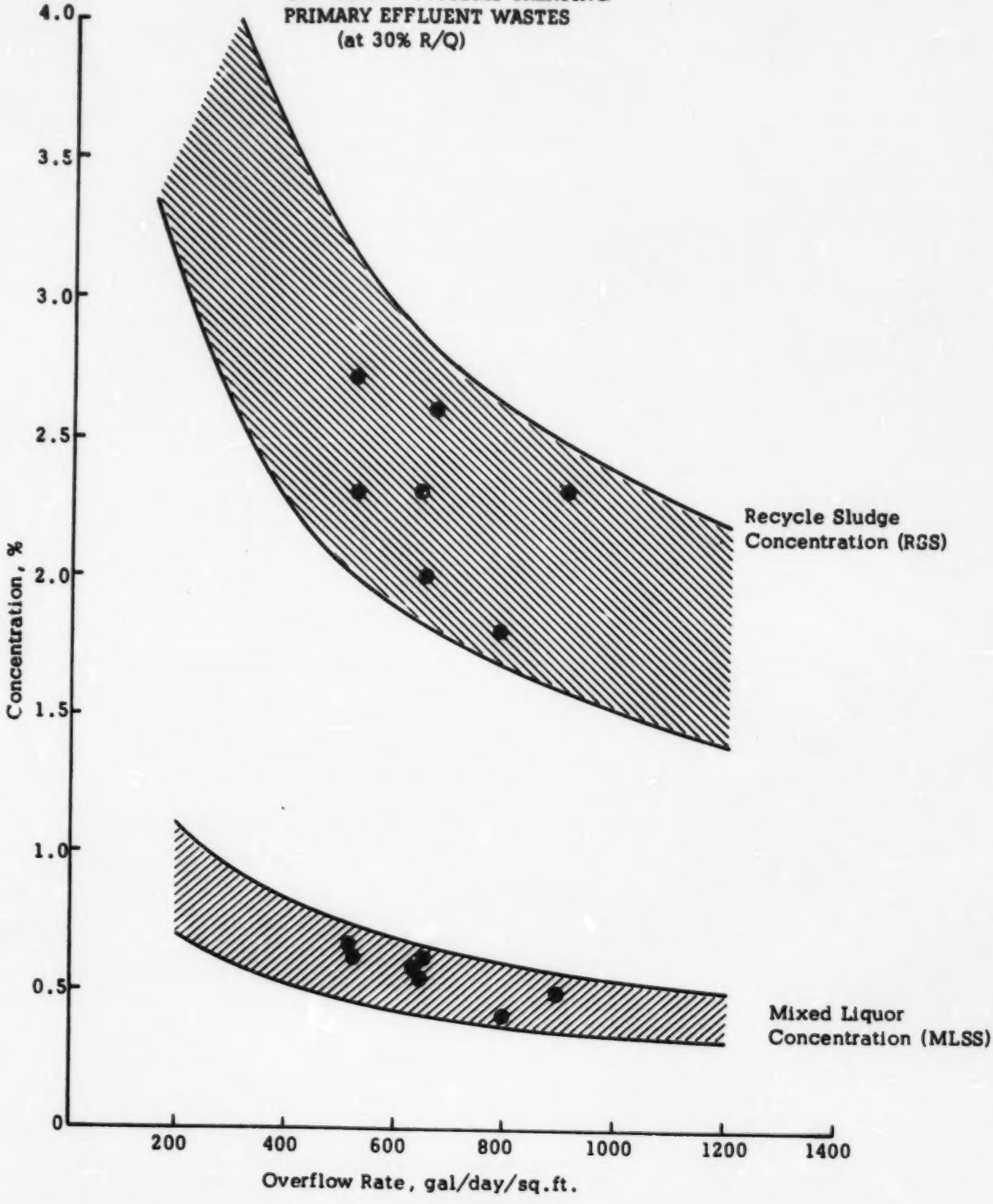
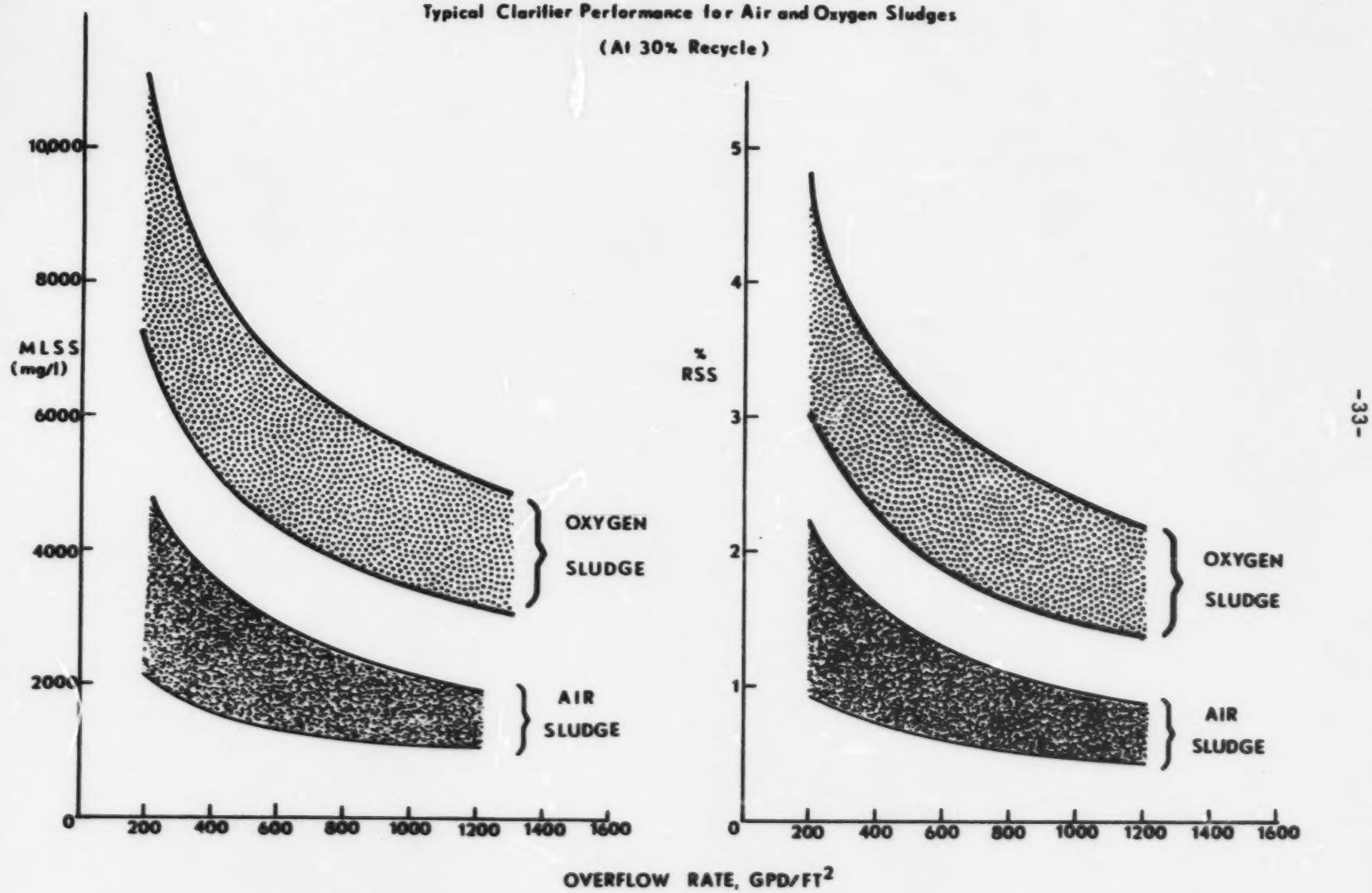


FIGURE 9

Typical Clarifier Performance for Air and Oxygen Sludges

(At 30% Recycle)



IV. PROCESS DESIGN

A. Required Process Information

The proper design of any secondary waste treatment process requires certain basic information concerning the waste to be treated and the UNOX System is not an exception. In general, this information can be classified as (1) wastewater quantity, (2) wastewater quality, (3) effluent quality required and (4) definition of the other unit operations or existing facilities in the treatment plant and their relationship to the secondary system. Table 8 generally depicts the required data. The following paragraphs elaborate on each of the aforementioned categories and outline where the information is most likely to come from. It will be apparent that it is not always possible to obtain all the required information and, therefore, it is usually necessary to make some judgments and consequently build some conservatism into the design to account both for inadequate and potentially inaccurate data. However, the degree of conservatism required can be better assessed by a recognition of those parameters which affect process performance and the resultant appreciation for the quantity of missing information.

Wastewater quantity is, of course, characterized by the rate of flow. Since this rate varies with time it is necessary to have information on the daily diurnal fluctuations as well as the average and peak flows during the year. This information is generally an extrapolation of existing information into the future and in some instances where no facilities presently exist it is a forecast based on experiences at similar facilities located elsewhere. This information is supplied by the customer's engineer and is used, along with process char-

TABLE VIII

DEFINITIONAL PARAMETERS

1. Wastewater Quantity: Maximum Month-Design Year
   - Average Flow, MGD
   - Maximum 4 hour Sustained Peak Flow, MGD
   - Design Flow, MGD

2. Wastewater Quality:
   - Average BOD_5, mg/l
   - Maximum Sustained (coincides with max. flow), mg/l
   - Design BOD_5, mg/l
   - COD/BOD_5 all cases
   - Source
   - Preceeding Treatment
   - Average Suspended Solids, mg/l
   - Average Volatile Suspended Solids, mg/l
   - Temperature, °C
   - pH
   - Alkalinity, mg/l as $CaCO_3$
   - Alpha, Beta
   - Nutrient Content, mg/l N, P
   - Heavy Metals
   - Other Toxic Components

3. Required Effluent Quality:
   - BOD_5, mg/l
   - SS, mg/l
   - N, mg/l
   - P, mg/l
   - COD, mg/l

4. Site Limitations
   - New or Existing Tankage
   - Land Area Available
   - Piling Required
   - Maximum Tank Depth, ft

5. Solids Handling Equipment:
   - Dewatering
   - Sludge Disposal

6. Secondary Clarifier Specifications:
   - Overflow Rate at Design Flow, gpd/ft^2
   - Depth, ft
   - Feed
   - Take Off
   - Sludge Return
   - Circular or Rectangular

acteristics, to ascertain a "design" flow and corresponding peak and minimum flows.

The phrase "wastewater quality" is used herein to describe characteristics of the wastewater which result from the components contained in it and includes such familiar parameters as five day Biochemical Oxygen Demand (BOD_5) and Chemical Oxygen Demand (COD). These parameters measure the oxygen requirements of the wastewater. The diurnal variations and annual average and peak values should therefore be known to accurately quantify the instantaneous and average oxygen demands in the secondary system. These values are also supplied by the customer's engineer and along with the "design" flow serve to define a design loading usually expressed in pounds of BOD_5 per day. Another parameter which helps to characterize the wastewater is the source. Is it municipal, or partially or totally industrial and what is the industry involved? Also important, especially as it effects the expected settling character of the mixed liquor and the quantity of waste activated sludge to dispose of, is the treatment preceding the secondary system. If the waste is only degritted the mixed liquor suspended solids will settle better and will contain a lower volatile fraction than if the waste has received primary settling. Also, more waste sludge will leave the secondary system if no primaries exist. Other important "quality" parameters are temperature (average and range), pH, alkalinity, total and volatile suspended solids level, alpha and beta values for the sewage, nutrient content, and the expected concentration of heavy metals or other components which are potentially toxic to the secondary system biomass. The above parameters are also to be supplied by the customer's engineer.

Another "quality" parameter which is best determined by pilot plant operation is the oxygen consumption requirements in terms of the amount required for biomass synthesis and endogeneous metabolism both of which occur during the removal of the pollutant material. In many cases, the waste stream does not presently exist or it is known that additional streams will alter its character in the near future so pilot plant results would not necessarily be representative of those to be expected in full scale operation. It is situations such as this where the very large amount of UNOX System pilot plant data on a variety of waste streams becomes especially useful. As can be seen from Figure 5, the oxygen consumption requirements are related to the food to biomass ratio.

The same discussion used in regard to the oxygen requirement can also be used to describe the mixed liquor settleability and the biokinetic characteristics of the wastewater which must also be known and can best be determined from pilot plant data. They too can be estimated based on broad pilot plant experience and the known source of the wastewater (see Figure 7 for settleability).

The effluent quality required is defined by the customer or his engineer and is usually based upon receiving stream standards or state regulations for removal. Parameters such as BOD_5, SS, TKN and phosphorus are usually involved. This required effluent quality must, of course, be known by the designing engineer as it dictates the extent of the required treatment. In the extreme, it may not be possible to attain the required effluent quality with a secondary system in which case some form of additional treatment

would be required.

The remaining information required pertains to specific site limitations and prior and subsequent unit operations which the customer's engineer is planning to specify. Among the site limitation information required is whether the job is conversion of existing tankage to upgrade the plant capacity or installation of new tankage. Also, it must be known whether or not land area is limiting and what limitations must be placed on tank depth and area due to water table level and piling requirements. The prior and subsequent unit operations are important in that they influence the character of the waste fed to the secondary system. Most sludge handling systems have supernate streams which are returned to either the primary or secondary systems and, depending on the system in question, these may have a noticeable effect on the character of the waste entering the secondary system.

The secondary clarifier is of extreme importance in the operation of a secondary treatment system, and the designer of the secondary system must know the overflow rate, depth, feed mechanism, takeoff mechanism and sludge return mechanism which the customer's engineer intends to install. The UNOX System will perform well with the same clarifiers as are used for a conventional air system, but since the clarifier itself has such an important effect on the expected underflow concentration and the mixed liquor suspended solids concentration, its design must be known so that the UNOX System can be properly integrated with it.

B. Oxygenation Tankage Design

The first major step in preparing a process design for a UNOX System lies in the selection of what may be termed independent variables. These variables may be called independent because selection of one does not automatically reduce the freedom of selection of the others due to the interrelationships in the process. The basic independent design variables are clarifier overflow rate, recycle ratio, food to biomass ratio, the MLVSS concentration, and aeration tank geometry. For conventional gravity secondary clarifiers the MLVSS concentration is of course directly related to the secondary clarifier design. The sludge settling characteristics, the clarifier overflow rate, and the recycle fraction directly determine the MLVSS levels attainable in the oxygenation tank as has been discussed previously.

The food to biomass ratio is initially selected at a value at which the system will operate properly in terms of required removals both at design and sustained peak loadings. The range of food to biomass ratios under which UNOX Systems have been run at high removal efficiencies on a variety of wastes is shown in Figure 3. The design level food to biomass ratio is selected such that the sustained peak food to biomass ratio lies within the range of proven operation. Typically, the peaks and design points will be such that the "design" food to biomass ratio is between 0.5 and 0.8. Following selection of the food to biomass ratio at the design point it remains only to determine the mixed-liquor volatile suspended solids level to have dictated the required aeration tank volume. This mixed-liquor volatile suspended solids level (used as a measure of the viable organisms in the mixed liquor) is, of course,

dependent upon the total mixed-liquor suspended solids level which, in turn, is dependent on the clarifier overflow rate, recycle ratio, type of waste, and type of pretreatment. Figure 9 shows the expected clarifier underflow concentrations for UNOX Systems as a function of overflow rate at a given recycle ratio. As discussed previously, the type of waste and the pretreatment received will dictate where within the band of expected underflow concentration the case being considered will fall. Once a recycle ratio has been specified and a value of underflow concentration determined, mixed-liquor liquor suspended solids level is determined by material balance (ignoring influent solids and the net solids production within the aeration tanks relative to the amount of solids present in the recycle stream (see Figure 8).

The selection of the recycle ratio is done as follows. The higher the recycle ratio the higher the mixed liquor solids concentration will be (up to about 100 percent recycle) but the lower the clarifier underflow concentration will be and the more difficult subsequent treatment of the waste activated sludge becomes. The recycle ratio should be selected to maximize the mixed-liquor suspended solids concentration recognizing that clarifier underflow concentration will diminish as recycle fraction increases. A value of 0.3 for the recycle ratio typically is selected for a UNOX System design.

Once the mixed-lqiuor suspended solids concentration has been determined, the volatile fraction must be ascertained in order to specify the system volume. Pilot plant data is the best source for this information and as can be seen from Tables 3 - 7, values for degritted waste can vary from 0.66 to 0.83, and for primary treatment waste from 0.72 to 0.90. In the absence of specific

pilot plant data and due to the large quantity of UNOX System pilot plant data, a good judgment as to the expected value for the volatile fraction can be made by knowing the waste source.

Knowing the "design" point BOD_5 load, food to biomass ratio, and mixed-liquor volatile suspended solids level, the detention time (based on raw flow) is fixed and given the design flow so is the oxygenation tank volume. With the information in hand concerning land area restriction, piling requirements, restrictions imposed by existing tankage, etc., the economic tank depth can be ascertained. Thus, the area of the tankage is determined and it remains only to specify the number of parallel bioreactors and the number of stages per bioreactor to have completely specified the oxygenation tankage. Generally, at least two parallel bioreactors are used with at least three stages per bioreactor.

C. Oxygen Requirements

As previously mentioned, the oxygen requirements for a UNOX System depend on both the COD to BOD_5 ratio of the feed wastewater and the food to biomass ratio under which the system is to operate. Figure 5 depicts the quantitative dependence on F/M as determined from the many pilot plant programs. Given the value of the COD to BOD_5 ratio and the food to biomass ratio as previously specified, it is possible to determine the expected consumption ratio (pounds of oxygen consumed per pound of BOD_5 removed) for the wastewater to be treated. Given the design flow, BOD_5 feed concentration to the secondary system, and required removal, the pounds of oxygen consumed per day is determined. If (as is typically the

case from economic considerations) about 90 percent utilization of the oxygen is specified, the tons per day of oxygen which must be generated at the design point is fixed.

D. Oxygen Supply

Following determination of the quantity of oxygen which must be generated to satisfy the wastewater demands, it is necessary to specify the type of oxygen generator which will best serve the needs of the plant. Two basic oxygen generator designs are employed to most economically and practically supply the wide range in oxygen demands which result from the wide range in size of wastewater treatment plants. These are the traditional cryogenic air separation process for the larger size applications and a pressure swing adsorption (PSA) system for the somewhat smaller and more common plant sizes.

The standard cryogenic air separation process involves the liquefaction of air followed by fractional distillation to separate it into its components (mainly nitrogen and oxygen). Figure 10 shows a schematic diagram of this process. The entering air is first filtered and compressed. It is then fed to the reversing heat exchangers which perform the dual function of cooling and removing the water vapor and carbon dioxide by freezing these mixtures out into the exchanger surfaces. This process is accomplished by periodically switching or "reversing" the feed air and the waste nitrogen streams through identical passes of the exchangers to regenerate their water vapor and carbon dioxide removal capacity. The air is next processed through "cold end gel traps" which are adsorbent beds which remove the final traces of carbon

FIGURE 10

FLOW DIAGRAM OF A CRYOGENIC OXYGEN GENERATING SYSTEM

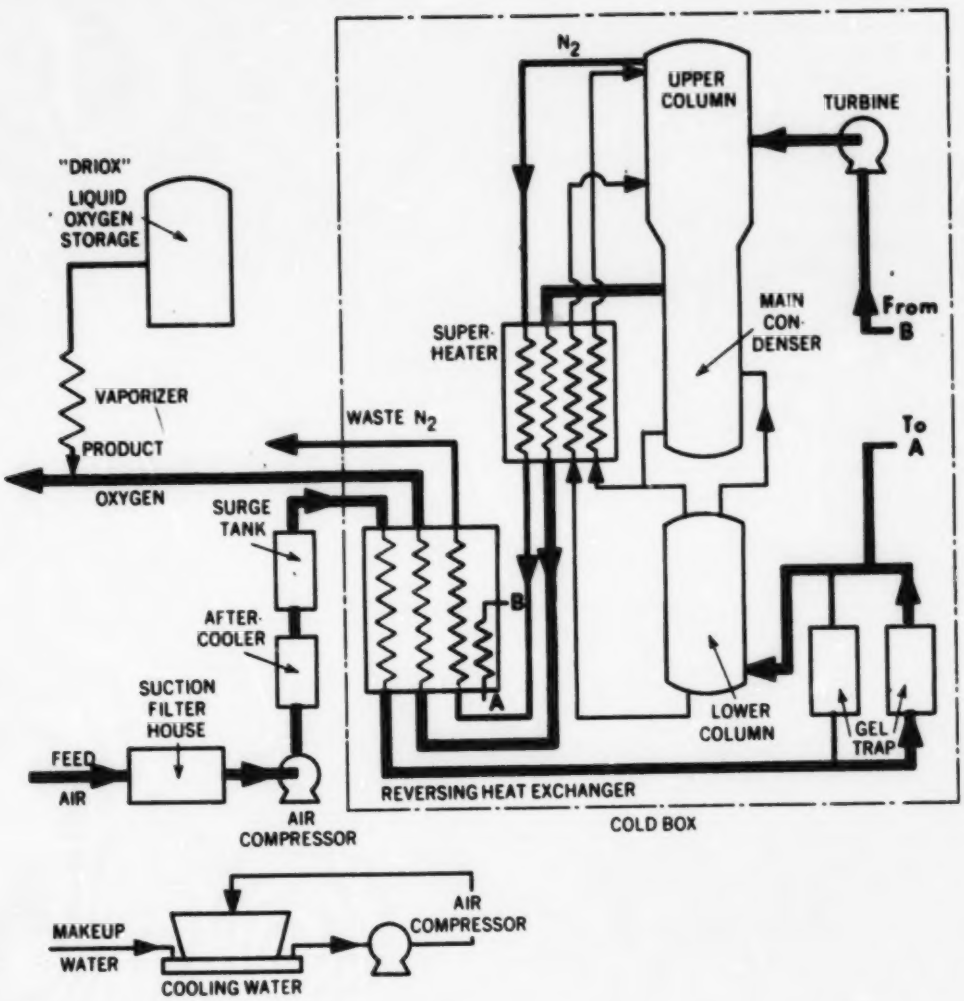
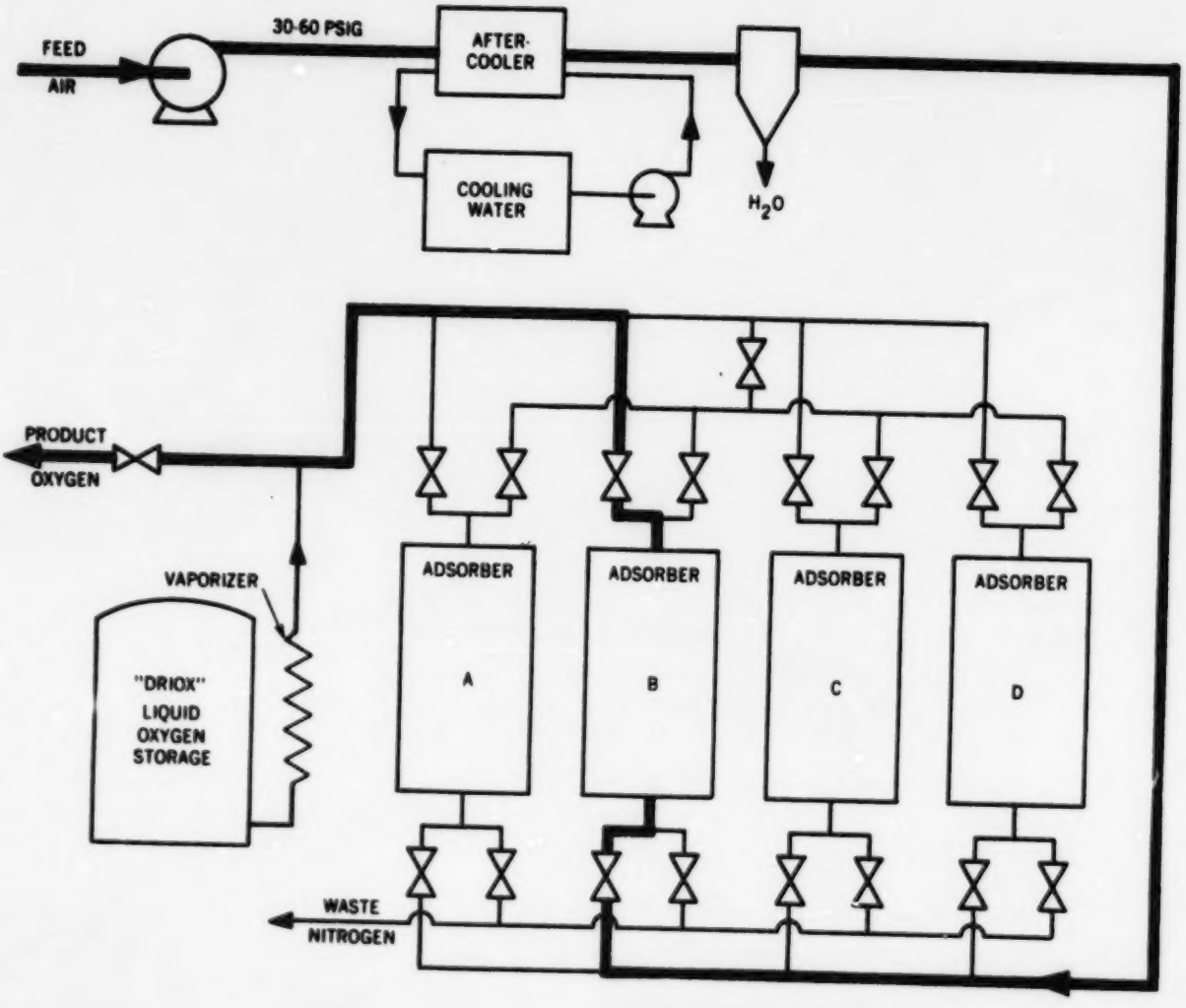


FIGURE 11

FLOW DIAGRAM OF A PSA OXYGEN GENERATING SYSTEM



PRESSURE SWING ADSORPTION UNIT

dioxide as well as most hydrocarbons from the feed air. It is then divided into two streams, one of which feeds directly to the "lower column" of the distillation unit. The other stream is returned to the reversing heat exchangers and partially warmed to provide the required temperature difference across the exchanger and is then passed through an expansion turbine and fed into the "upper column" of the distillation unit. An oxygen rich liquid exists from the bottom of the "lower column" and the liquid nitrogen from the top. Both streams are then subcooled and transferred to the upper column as shown in Figure 11. In this column the descending liquid phase becomes progressively richer in oxygen until that which collects in the condenser reboiler is the oxygen product stream. This oxygen is continually recirculated through an adsorption trap to remove all possible residual traces of hydrocarbons. The waste nitrogen exists from the top portion of the "upper column" and is heat exchanged along with the oxygen product to recover all available refrigeration and to regenerate the reversing heat exchangers as discussed above.

The PSA System utilizes a multibed adsorption process to provide a continuous flow of oxygen gas. Figure 11 shows a schematic diagram of the four bed embodiment. The feed air is compressed and passed through one of the adsorbers. The adsorbent removes the carbon dioxide, water and nitrogen gas, producing a relatively high purity oxygen product. While one bed is adsorbing, the others are in various stages of regeneration. The PSA oxygen generator operates on a pressure swing adsorption concept in which the oxygen is separated from the feed air by adsorption at "high" pressure (30-60 psig) and the adsorbent is regenerated by "blow down" to low pressure.

The process operates on a repeated cycle having two basic steps, adsorption and regeneration. During the adsorption step, feed air flows through one of the adsorber vessels until the adsorbent is partially loaded with impurity. At that time the feed air flow is switched to another adsorber and the first adsorber is regenerated. During regeneration the impurities are cleaned from the adsorbent so that the bed will be available again for the adsorption step. Regeneration is carried out by depressurizing to atmospheric pressure, purging with some of the oxygen, and repressurizing back to the pressure of the feed air.

As discussed above, the driving force on the oxygen gas generator is a simple, relatively low horsepower air compressor. An obvious and totally acceptable form of overall system backup would therefore be a spare feed air compressor. This would supply essentially 100 percent backup capability. A more desirable, effective, and flexible form of oxygen supply backup, however, can be obtained through the use of on-site, liquid oxygen storage in conjunction with the on-site gas generator. This backup is in the form of from one up to several days production capacity of liquid oxygen storage. This method not only provides absolutely fail-safe backup to the on-site oxygen gas generator, but it also adds the capability of instantaneous delivery of substantial additional oxygen capacity to the aeration tanks to handle peak load conditions. Such peak or above average loads could otherwise be handled only by substantially oversizing the oxygen generator.

Both PSA and cryogenic plants have efficient turndown capability with the PSA units being capable of turning down with only a small loss in efficiency throughout the entire range of their production capacity. Although the cryogenic plant cannot turn down as far, it does have the capability to produce liquid oxygen during low load periods. This liquid can be stored and used to supplement the plant during periods of high load. Therefore, although the cryogenic plant cannot turn down "all the way", it can be installed at a capacity somewhat less than the sustained peak would demand.

E. Operating Power Requirements

Given the basic gas-liquid mass transfer capabilities for the dissolution equipment selected, the operating horsepower for oxygen transfer can be determined from the oxygen gas phase concentrations, oxygen consumption requirements, the wastewater alpha and beta values, the temperature, and the operating D.O. level. The gas phase concentration varies throughout the system with the highest concentration (highest transfer driving force) being present at the front end of the system where the highest demand exists. Thus, in comparison with air systems, a 4 to 5 fold increase can be attained in the latter stages where the gas is vented at 40 - 60 percent oxygen concentration.

Once the dissolution power requirements have been determined, a check should be made to be sure that sufficient energy is being supplied with the selected dissolution equipment to maintain proper mixing biomass in suspension. Generally speaking, if the equipment can maintain sufficient bottom velocities throughout the tank, mixing should be adequate. If it is

found (as will often be the case with a weak waste) that sufficient bottom velocity will not be maintained, additional horsepower must be added, and the system is said to be mixing limited. Brake horsepower requirements for dissolution and mixing in a UNOX System typically run from 0.08 to 0.14 HP per 1000 gallons of mixed liquor under aeration depending on the waste strength, the degree of mixing limitation, the feed oxygen purity used, and the mass transfer capability of the dissolution equipment.

F. Sustained Peak Loads

Most waste treatment plants experience, a few times during the year, waste loads which can be described as the "sustained organic peak loading". This loading is the maximum organic loading (pounds of BOD_5 per day, includes the combination of flow and concentration) which the plant sees for a sustained period usually in excess of four hours. As this four or more hours is sufficient to "upset" the system for substantially longer than the period of occurrence if essentially zero D.O. conditions prevail in the oxygenation tanks, the oxygenation system should be designed to maintain 1-2 mg/l of D.O. in the system in the first stage of the system during these "peak organic loading" periods. The UNOX System has several inherent characteristics which allow it to handle these "peak" conditions. At peak load conditions, UNOX Systems are designed to maintain approximately 6 mg/l D.O. in the mixed liquor. In the event of an unusually severe short duration peak the ability to transfer about 30 percent more oxygen into the mixed liquor is achieved if the D.O. level decreases to 1 - 2 mg/l. Also, because liquid oxygen is available for backup purposes with the same supply

capacity as the installed plant, it is possible to double the oxygen plant flow to the oxygenation tankage. Assuming the oxygen plant is designed to supply enough oxygen for the sustained peak condition with a 90 percent utilization, it is therefore possible to decrease the utilization to less than 50 percent. This results in a much increased average oxygen gas phase concentration with a resultant increase in dissolution capacity. Although this is not an economic mode of operation over extended periods of time, for short term operation it can be quite effective. Both of these methods for increasing dissolution capacity function by increasing the driving force for mass transfer. The first reduces the mixed liquor D.O. while the second increases the oxygen saturation concentration in the mixed liquor. Neither of these options are available to an air system since the design D.O. level is usually already at 1 or 2 mg/l and the oxygen concentration of air is fixed.

As the load on a plant increases, the food to biomass ratio increases at least proportionately. If only the BOD_5 concentration increase is responsible for the peak condition and the flow remains the same, the mixed liquor volatile suspended solids level will remain substantially the same and the food to biomass concentration will indeed increase by the same amount as the organic load. If, as is more commonly the case, the increase in organic load is a result of both flow and concentration increases or flow increases alone, the clarifier overflow rate will increase and the mixed-liquor suspended solids level will decrease. This results in a food to biomass ratio which is increased by some amount greater than the increase in organic load. Due to

the ability of the UNOX System to obtain good removals over such a wide range of food to biomass ratios (see Figure 3), this increase in food to biomass ratio will not be detrimental to system performance as long as the required oxygen can be supplied. However, as can be seen from Figure 5, an increase in food to biomass ratio can result in a substantial decrease in the oxygen required per pound of BOD_5 removed as more biomass is formed and less endogenous respiration occurs.

With the capability to transfer more oxygen than at the design point and the fact that a decrease in consumption ratio usually occurs at the sustained peak condition, the UNOX System has the capability to handle organic loads from two to two and one half times the design organic loading while still maintaining completely aerobic conditions in the aeration tankage.

G. Activated Sludge Waste Quantity

The two parameters of major importance in sizing of sludge dewatering and solids disposal systems are the pounds of waste solids per day and the concentration of solids in the waste stream. The former obviously indicates the solids which must be disposed of while the latter is indicative of the volume of waste which must be treated. The pounds of solids which must be wasted per day to prevent accumulation in the system is dependent on several parameters. The biomass is producing new biomass in the process of removing BOD_5. The ratio of the biomass synthesized to the BOD_5 removed is known as the yield coefficient. Endogeneous respiration is also occurring at a rate proportional to the number of viable organisms in the

mixed liquor and this results in the destruction of some of the organisms. Since the endogenous respiration is proportional to that fraction of the mixed liquor volatile suspended solids which is active biomass. The percentage of active biomass in the mixed liquor will be, in part, dependent upon the stresses put on the system. Thus, maintenance of relatively constant environmental conditions should result in an increased fraction of active biomass and thus less overall sludge production. The maintenance of relatively constant environmental conditions is, of course, an inherent characteristic of a UNOX System.

Other parameters affecting the quantity of solids which must be wasted from the system are the quantity of nondegradable solids (both volatile and nonvolatile) that enter the system with the influent sewage, and the quantity of solids which leave the system in the effluent stream. Therefore, the pounds which must be wasted from the system are the pounds produced by synthesis during BOD_5 removal, plus the pounds entering the system as nondegradable volatile and nondegradable nonvolatile solids, minus the solids destroyed by endogenous respiration, minus those lost from the system in the effluent.

Figure 6 indicates the pounds of excess volatile solids formed per pound of BOD_5 removed as a function of sludge retention time (sludge age) as observed at several UNOX System pilot plant locations. The results include the effect of temperature (some plants were run in the south in the summer with resulting low production and others in the north in the winter with higher production rate) variations in nondegradable volatile solids in

the influent from plant to plant, as well as the yield and endogenous decay effects. Given the desired SRT, the temperature of interest, and the expected quantity of nondegradable volatile solids in the influent sewage it is possible to estimate from Figure 6 the pounds of excess volatile suspended solids which will be produced. Given this, the expected suspended solids in the effluent and the ratio of the volatile suspended solids to the total (see Tables 3-7), the pounds of solids which must be wasted daily can be estimated.

It remains to determine the gallons per day of the waste stream and this can be done given the information previously presented. The clarifier underflow concentration was determined in assigning the mixed-liquor suspended solids level. This concentration of the waste stream and the pounds of solids wasted per day fixed the gallons wasted per day. A highly concentrated waste stream, such as the one that can be obtained from a UNOX System sludge, can have value in decreasing the costs associated with sludge handling and disposal.

V. PROCESS SAFETY

A. Oxygen Gas

In a UNOX System, oxygen is delivered to the system in a relatively pure form, and contact with the mixed-liquor takes place in a closed system. For these reasons a few routine safeguards are necessary to ensure a totally safe wastewater treatment system.

Oxygen itself is not dangerous, it is colorless, odorless, and tasteless, and supports combustion. A flame burning in pure oxygen combusts at a more rapid rate than in air because of the absence of nitrogen as a diluent. It is a common fallacy that the combination of oxygen and combustible material will spontaneously ignite. The lower explosive limits (LEL) of all commonly found hydrocarbons are almost exactly identical in an oxygen or air atmosphere. Furthermore, for ignition to take place, a spark must be present, as auto ignition does not occur. Thus, the safeguards built into a UNOX System are not to protect against oxygen gas, which is not dangerous by itself, but to prevent a build-up of combustibles in the gas space in the covered aeration basin.

B. Oxygen and the UNOX System

Oxygen enters the oxygenation tank, where a gauge pressure of 1 to 4 inches of water is maintained, and mixes with the wastewater. After entering the oxygenation tank, the high purity gas (90-100 percent oxygen) passes through a series of wastewater treatment stages and is vented to the atmosphere with approximately a 40 to 50 percent oxygen concentration. The process gas in the aeration tank presents a safe environment, because it is at low pressure (several inches of water), ambient termperature, and is saturated with water vapor.

All equipment and materials having to do with the storage and handling of oxygen are carefully selected for oxygen compatibility. In this connection, the mechanical, electrical, and control equipment are located in the open atmosphere, avoiding the high oxygen concentrations under the tank cover. Because of the low pressures in the process, it is highly unlikely that an oxygen leak could create a hazard to equipment or personnel by creating high oxygen concentrations.

The possible presence of combustible materials in wastewater from gasoline or oil spills and industrial plant upsets is well known to treatment plant operators. Although such spills may occur, dangerous volatile hydrocarbons are not expected to reach the UNOX System for several reasons. These materials are only sparingly soluble in water and tend to be easily stripped from the wastewater by contact with the atmosphere. Volatile materials such as gasoline would, therefore, normally be stripped from the wastewater in the sewer lines before entering the treatment plant. At the treatment plant itself, these volatile materials would further be removed in an existing comminutors, screen chambers, grit chambers, or primary clarifiers before entering the UNOX System.

The presence of volatile hydrocarbons in the oxygen-rich gas space of the UNOX System aeration tank is not a sufficient condition to constitute a hazard; a source of ignition is also required. The UNOX System components are designed to eliminate any potential ignition sources. As discussed earlier, no electrical components are installed under the tank cover, and no metal to metal contact of moving parts is present.

Even though both an ignition source and a fuel in concentrations exceeding the LEL are required for a hazard to exist, it is the policy

in designing a UNOX System to eliminate both. To this end, combustible gas analyzers are employed in the aeration tankage to continuously monitor the process gas for the presence of combustible material. Should an approach to an LEL limit occur, the analyzer activates the necessary controls which cause the gas space to be purged with air thereby preventing a build-up of the combustible vapors to a level greater than 50 percent of the LEL. The purging continues until the gas and liquid have carried the combustible material out of the system.

Greases and oils are also commonly present in both municipal and industrial wastewaters. These substances have low volatility at wastewater temperatures and pass through the system with as much bio-oxidation and decomposition as normally obtainable in a biological treatment process. They are not combustible under these conditions.

VI. UNOX SYSTEM SCOPE OF SUPPLY

A. General

In general, the scope of supply for a UNOX System includes oxygen dissolution equipment, oxygen generation equipment, and appropriate controls and instruments to mate the two subsystems in an efficient, reliable, and safe operating mode. The scope of supply does not include concrete work, deck covers, and in many cases, installation of the above mentioned equipment. All engineering work necessary to design and provide a workable UNOX System is performed in cooperation with the customer and/or his consulting engineer.

The UNOX System dissolution equipment will in general be either surface aerators or submerged turbines depending upon economic considerations. Generally speaking, where deep tanks offer an advantage over shallow and the waste stream is large in quantity and high in strength, a submerged turbine system will be preferable. Therefore, again in the general case, it can be expected that the greatest number of UNOX System's will employ surface aerators while the largest sized applications may well utilize submerged turbines. Because of the complexity inherent in large jobs, it is often the policy to offer these UNOX System's on an "installed by UCC" basis while the smaller jobs can be more cost effective on an uninstalled basis. As has been previously mentioned, the cryogenic oxygen supply is often more cost effective for large plants, and the PSA for smaller ones. The most common combinations will therefore be surface aerators with PSA oxygen and submerged turbines with cryogenic oxygen. The following paragraphs outline a typical "scope of supply" for each of these combinations with the surface aerator - PSA combination preceeding the submerged turbine cryogenic oxygen combination.

B. Surface Aerator - PSA System

1. Dissolution Equipment

The number of units specified in the design will be supplied. Each will be designed to be assembled as a complete unit ready for installation through openings in the tank covers. Each assembly will consist of:

a) Motor, speed reducer, lube system

b) Shaft and aerator blade

c) Mounting skid and shaft seal

All equipment and materials are designed to provide long maintenance-free service. The speed reducers are specified to have an overall AGMA service factor of two, while other components critical to the continuous operation of the assembly are designed for service factors of up to five. Gearing and bearings of proven quality are used throughout the speed reducer assembly. The gearing has a service factor of two plus 200% overload rating capabilities. The anti-friction bearings are designed to the AFBMA (B-10) life rating of 75-100 thousand hours, depending on the severity of the application. All components submerged in the mixed-liquor are made of stainless steel or other materials proven to give prolonged service in the mixed-liquor environment.

2. Pressure Swing Adsorption Equipment

The oxygen generation plant is an automatically controlled unit. It is made up of an adsorption unit and a compressor unit. The adsorption unit is designed as a complete package containing adsorbent vessels, valve and piping skids, and controls. The vessels contain

sufficient adsorbent, supplied by Union Carbide, to upgrade air to the desired purity. The vessel design is such so as to minimize air losses.

The valve and piping skid contains pneumatically operated automatic valves mounted directly on the skid. The valves selected have been demonstrated to be leak tight after one to two million cycles. In addition, the PSA skid contains all necessary valves and controls required for flow and pressure control. It also contains local instrumentation.

An air drier is provided to dry the air used for the instrumentation. This drier is mounted on the PSA unit skid. The drier is suitable for outdoor installation and is capable of automatic operation.

The compressor unit is completely assembled on a common skid and ready for immediate mounting on a concrete foundation. This skid assembly includes a non-lubricated compressor, electric motor driver, aftercooler, moisture separator, discharge pulsation dampener (if required), inlet air filter, high discharge temperature and pressure shut-down switches, lube system, and all interconnecting piping and valves. A separate skid will contain the cooling system. The equipment provided is of the highest quality and is designed to operate for many years with only routine maintenance. It is also suitable for unprotected outdoor installation and includes any special protection or provisions necessary to provide continuous year-round operation.

C. Submerged Turbine - Cryogenic System

1. Dissolution Equipment

The oxygenation tank(s) will be fitted with the number of

mixing and oxygen dissolution assemblies specified in the design. Each mixing assembly consists of an electric motor driven speed reducer, propeller, and gas injection sparger totally integrated and assembled to a base plate which bolts to the tank cover. All equipment used is designed to provide long, maintenance-free service. The speed reducers are specified to have an overall AGMA service factor of two, while other components critical to the continuous operation of the mixing assembly are designed for service factors of up to five. Gearing and bearings of proven quality are used throughout the speed reducers. The gearing has a service factor of two plus 200% overload rating capabilities. The anti-friction bearings are designed to the AFBMA (B-10) life rating of 75-100,000 hours, depending on the severity of the application. All components submerged in the mixed-liquor are made from stainless steel or other materials proven to give prolonged trouble-free service in the mixed-liquor environment. The entire mixing and oxygen dissolution assembly is instrumented with simple but reliable monitors which will set off an alarm in case of potential problems and/or shut down equipment before any component failure has taken place.

The oxygen gas injection to the mixed-liquor is accomplished by low pressure oxygen compressors. These machines can be located on the tank covers either outdoors or in a small building provided on or near the tanks. Each compressor is manifolded to deliver oxygen gas to all similar stages in the tanks. These compressors are designed to the same high standards as the mixing assemblies and similarly instrumented to warn of possible impending problems. Automatic shutdown of any unit is provided before extensive damage can occur to the machinery. Automatic

shutdown of equipment is a feature afforded only in the UNOX System since process backup is provided by the other equipment on stream.

2. Cryogenic Oxygen Generation Plant

The oxygen generation plant is an automatically controlled unit. It is composed of the following major components:

- Air suction filter house.
- Centrifugal air compressor, driven by a electric motor, with interstage cooling after each stage.
- Air surge tank to absorb the cyclic variation in air flow to the reversing heat exchangers.
- Air separation unit or cold box consisting of a column and reboiler, gel traps and superheater, and reversing heat exchangers. The cryogenic equipment is installed in cylindrical casings fabricated from carbon steel, perlite insulated, and maintained under a slight positive pressure to prevent moist air from entering the insulation space. The cold box is factory fabricated with most internal parts made of aluminum.
- A cryogenic expansion turbine. Process air is admitted radially inward through variable area nozzles, expanded in the turbine impellers, and exhausted axially. The impeller shaft is directly connected to the blower. The turbine seal gas system and the turbine lube oil system are supplied with the turbine. Oil temperature is controlled and backup for turbine coastdown is supplied by an oil filled, pressurized accumulator.

- One thaw heater assembly to thaw the cryogenic cold box including gel traps during turnarounds.

- A cooling tower to supply required intercooler, and aftercooling of the gas leaving the air compressor.

In addition to the above listed major components, all the instruments, piping, controls and instrument panels necessary to make this plant functional are included.

D. Instrumentation

1. An integrated control system is included which automatically controls the oxygen gas flow to match the demand of the oxygen load on the system. The oxygen generating plant increases or decreases its output automatically in response to the system.

2. A main panel is supplied with a vent gas analyzer and indicator, a combustible gas analyzer and recorder, a feed gas flow controller and a central alarm which will sound in case of an impending malfunction of the unit.

3. Stage pressure/vacuum relief devices are provided, as are appropriate shutdown switches for the mechanical equipment.

E. Oxygen Backup Facilities

A Driox storage tank and vaporizer will be provided with capacity for at least 24 hours of oxygen backup at the rated generation plant product automatic flow.

F. Union Carbide Engineering Support

The engineering services provided by Union Carbide Corporation will include the following:

1. UNOX System process design
2. UNOX System equipment design
3. UNOX System equipment procurement
4. Consultation on tankage and cover design and installation
5. Consultation on UNOX System installation
6. Assistance in checkout of equipment and startup of the UNOX System.
7. Training of plant operators.
8. Supply of instruction, operating and maintenance manuals for the UNOX System.
9. Definition of engineering interfaces between Union Carbide Corporation and the customer's engineer.

VII. ECONOMIC CONSIDERATIONS

The economics of oxygen in the activated sludge process relative to using a conventional air activated sludge process derive from the relative process differences which have been discussed in earlier sections of the report. Notwithstanding the process and operational advantages, the essence of the economic decision is that sufficient savings in investment and operating costs must be shown within the wastewater treatment plant as a system to justify the selection of oxygen. Thus, it is necessary to consider such costs as sludge handling and disposal, as well as the direct costs of installing and operating the activated sludge part of the waste treatment plant.

The direct economic factors governing the economics of oxygen versus air for the activated sludge process include the following:

(1) Higher mixed liquor solids under aeration can be maintained when using oxygen as the aeration gas, without occurrence of oxygen mass transfer limitations. Concentrating the active biomass in a smaller volume reduces concrete tankage requirements, and is a chief reason for expecting reduced costs from such a system. This effect can be extremely important when land is limited and when extensive piling work is necessary.

(2) Higher oxygen transfer efficiencies are made possible using oxygen as the aeration gas. This leads to less equipment requirements for oxygen dissolution with an attendant reduction in auxiliary equipment such as electrical switchgear.

(3) Power savings generally result from the higher oxygen mass transfer efficiencies experienced in pure oxygen processes. The power required to generate oxygen for the biological process added to that required for oxygen

dissolution is generally less than that required to provide oxygen to a conventional activated sludge process with air as the oxygen source.

The economics of oxygen are also governed by indirect considerations such as sludge handling and disposal and odor control.

(1) The improved settling characteristics of oxygen sludge result in the achievement of a much thicker clarifier underflow concentration than is achievable with conventional aeration systems at the same overflow rate. This allows the maintenance of higher mixed liquor concentrations, but also provides advantages in sludge handling and disposal since the waste solids from the secondary clarifier are available in a significantly decreased volume of liquid.

(2) Substantial evidence in many operating programs continues to indicate that less total pounds of dry solids will be produced with an oxygen process than with conventional aeration activated sludge. This also will effect the economics of sludge handling and disposal.

(3) The excellent flocculating characteristics of oxygen sludge which account for improved settling characteristics in a secondary clarifier also contribute to improved performance in sludge handling equipment such as centrifuges and vacuum filters.

(4) Odor control is frequently an important consideration in selection of oxygen for secondary treatment. Since nitrogen is rejected from the gas feed to the process before using the oxygen, and since 90% of the oxygen is utilized compared with about 5% for conventional air activated sludge processes, the total gas volume vented from an oxygen system is normally less than 1% of the volume vented from a conventional air process. This gas is vented at a single point as opposed to the entire surface area of the tank and, therefore, can be collected for further odor treatment if desirable.

The scope of supply of oxygen equipment for use in an activated sludge process is small relative to the equipment requirements required for a wastewater treatment plant. Union Carbide's scope of supply includes the oxygen generation plant, the equipment for oxygen dissolution, and the instrumentation and controls to integrate this equipment into the activated sludge process. Union Carbide does not supply concrete tanks or covers, clarifiers, liquid pumps and controls, or any sludge handling and disposal equipment, but rather prefers to work with the consultant to integrate the Union Carbide equipment into the equipment best supplied and constructed under the control of the consultant. Given this method of operation and the economic effects discussed earlier, it is of little or no value to discuss the cost of Union Carbide supplied equipment only. Rather, it is necessary to consider the overall economic consequences to the waste treatment facility of a decision to install oxygen for the activated sludge part of the plant. In practice this economic comparison is performed by the consultant as an integral part of his process evaluation and selection service to his client. Union Carbide participates by providing economic data covering its own scope of supply for each specific case. With such a procedure the total economics are rarely known to Union Carbide until the overall evaluation and selection process is complete and published. A few such evaluations are available and are summarized below.

Middlesex County, N. J.

A 300-day pilot plant program was conducted prior to process selection of UNOX by the Middlesex County Sewerage Authority and the consultant Metcalf and Eddy. The economics were prepared comparing complete mix air activated

sludge with oxygen for a 120 MGD plant. The results were published as follows:

	UNOX	Air Activated Sludge
Capital	$83,580,000	$104,020,000
Operating Cost/Year	7,390,000	8,290,000

Detroit, Michigan

The City of Detroit and the consultant Hubbell, Roth and Clark determined economics for their initial 300 MGD plant installation. For this portion of their ultimate 1200 MGD requirements their economic evaluation indicated a 20% savings for the aeration tank portion only. Their evaluation was based on a UNOX System compared with a 2.28 hour detention time air activated sludge system.

	UNOX	Air Activated Sludge
Capital	$39,500,000	$51,700,000
Operating Costs/Year	1,599,000	1,911,000

Oakland, California

A pilot plant program was recently completed at the East Bay Municipal Utility District plant in West Oakland, California. The UNOX System was selected for the West Oakland plant after meetings with the U.S. Environmental Protection Agency, the State Water Resources Control Board, and the Bay Area Regional Water Quality Control Board. In addition to economic considerations, UNOX was selected because the data indicated that pure oxygen was more reliable and provided a higher margin of safety in meeting Federal and State standards. The system also will serve as a building block for additional systems if additional water quality standards are imposed on the San Francisco bay dischargers in the future. Indicated costs for UNOX in comparison with a

chemical treatment and trickling filter process were given as follows:

	UNOX	Chemical Treatment plus Trickling Filter
Capital	$47,000,000	$56,000,000
Operating Cost $/Year	4,000,000	4,900,000

Euclid, Ohio

One evaluation has been released on a plant substantially smaller than the Detroit and Middlesex jobs. The Euclid, Ohio, design was prepared by Havens and Emerson for a plant size of 22 MGD. The published economics indicated a total capital savings of 20% for UNOX.

	UNOX	Air Activated Sludge
Capital	$10,000,000	$12,000,000
Operating Costs/Year	1,120,000	1,180,000

Union Carbide has attempted some economic analysis, however, generalization is difficult because of the many different circumstances existing in each specific location. The value of land, piling requirements, and method of sludge disposal among others always effect the specific case. The published economics in the EPA report covering the initial demonstration of oxygen at Batavia is an attempt at generalization. While the absolute numbers are certainly not applicable for every specific treatment plant, Union Carbide does find that the general conclusions appear valid. In general, the economic attractiveness of oxygen improves as plant size increases because large size oxygen generators are more cost effective. At this time oxygen has been selected at a number of plants in the 4 to 6 MGD range, but below that size economics have

not been favorable except in the industrial market, where high strength wastes are being treated. Union Carbide is currently completing technical and market development work of pre-engineered plants in the 1 to 5.0 MGD range employing pure oxygen. The projected installed costs for these plants are as follows. Costs as presented include all tankage and equipment, as well as installation.

Capacity, MGD	UNOX	Conventional Air
0.5	$130,000	$130,000
2.0	320-400,000	370-390,000
5.0	530-700,000	700-750,000

Pre-engineered UNOX plants can be offered with oxygen supply from liquid oxygen or from on-site oxygen generators. The operating costs of these plants are comparable throughout the range, and, therefore, oxygen systems can be expected to compete favorably with air systems at this plant size range.